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Fire Performance of Candidate Materials for a Next Generation Fire Attack Hose

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Major Qualifying Project Report

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Abstract

This research documents the thermal performance of fire-resistant materials for use in the outer jacket of a next generation fire attack hose. Current hose materials, polyester and nylon 6,6, have decomposition temperatures lower than those seen on the fireground. A unique test procedure was developed by the team using a cone calorimeter for its steady state radiative heat source that can simulate conditions seen on the fireground. Ten materials used in other high heat applications were identified and tested using this testing procedure. Results showed that materials can survive flashover and post-flashover conditions while current materials fail prior to flashover. This project is a stepping stone in the discovery and development of material testing for a next generation fire attack hose.

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Table of Contents

Table of Figures

List of Tables

Definitions (Oxford English Dictionary, N.D.)

Burn-through	*n.*	A hole formed in a material due to exposure to heat
Fire-resistant	*adj.*	able to withstand fire without damage or without structural failure
Fire-retardant	(a) *n.*	(a) a substance or treatment that confers the property of slowing or halting the spread of fire
	(b) *adj.*	(b) (usually with hyphen) that slows or halts the spread of fire
Flame-resistant	*adj.*	not readily flammable
Flame-retardant	*adj.*	See flame-resistant

1. Introduction

This section outlines and discusses the significance of this Major Qualifying Project (MQP) and the potential impact it may have on the fire industry.

1.1 The Problem

On March 26, 2014 a nine-alarm fire broke out in a four-story brick home in the Back Bay of Boston, Massachusetts. Strong winds drove an intense fire that continued to grow, tearing through the brownstone and resulting in unpredictable conditions. In the basement of the building were two Boston Fire Department officials, Lieutenant Edward Walsh and Firefighter Michael Kennedy. They entered the building with the intent of rescuing a possible victim from the basement. Upon reaching the bottom of the stairs, Lieutenant Walsh was recorded calling Command to request water. At this point, the Engine 33 pump operator charged the line. However, "the 1 ¾-inch hoseline used by Engine 33 was burned through during the initial fire-fighting operations. The 2 ½-inch hoseline that Engine 7 stretched to the first floor was severely damaged as well" (The National Institute for Occupational Safety and Health (NIOSH), 2016). Tragically, neither firefighter survived the incident.

1.2 Next Generation Fire Attack Hose Research Project

Professor Notarianni, in WPI's Fire Protection Engineering (FPE) Department, is the lead advisor for the Next Generation Fire Attack Hose Project whose objective is to facilitate the development of a fire hose that can withstand the rigors of the fireground. *Fire Performance of Candidate Materials For a Next Generation Fire Attack Hose* is one key part of this multi-year project in which, to date, six distinct student research teams are working on one or more key parts of this important research. The overall project has achieved several advancements in the areas of:

1) Incident Documentation/Creation of a National Database

2) Review of National and International Standards

3) Determining and Documenting the Needs of the Fire Service

4) Development of Taxonomy of Performance Metrics

5) Manufacturing

6) Engagement of Stakeholders

7) Documenting Heat Resistance of Current Hose Materials

8). Identification and Testing of Higher Performing Materials

9). Development of Standardized Testing Apparatus for Conduction

10) Development of a Standardized Testing Apparatus for Convection and Radiation

The Next Generation Fire Attack Hose Research Project has developed a database which tracks burn-throughs and has also determined that the current standards for the fire hose do not accurately reflect modern day fireground conditions. The number of incidents now documented in the database show that the Boston Back Bay tragedy is not a lone event and the database shows that burn-throughs are occurring more often than researchers thought.

Teams have analyzed NFPA 1961 *Standard on Fire Hose* and NFPA 1971 *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting.* Through this analysis, students determined that fire hoses are tested less vigorously than Personal Protective Equipment (PPE), even though they face the same conditions on the fireground. Research has also been conducted in relation to other standards, both internationally as well as within the United States. Communication with the fire service facilitated the creation of a taxonomy of metrics that a fire hose needs to meet.

Research on materials used to manufacture hoses was also conducted by another WPI MQP team. This team conducted initial tests on some candidate materials for use in hoses. In order to facilitate testing of fire attack hoses in a way that more accurately depicts fireground conditions hoses must withstand, the Fire Attack Hose Research Project is in the process of developing new test methods. Two teams are currently working to develop apparatuses to test hoses using conductive and convective heat transfer. These teams are working to develop and patent the apparatus and present the testing methods to the NFPA 1961 Technical Committee.

1.3 Investigation of Fire Performance of Candidate Materials - Project Goals

This project aims to investigate the thermal performance of materials that are currently used in other high heat environments as candidates for the outer jacket of a next generation fire attack hose. It was hypothesized that several candidate materials were available that could outperform current materials in terms of radiative heat performance.

2. Background

The following section highlights important information needed to convey how burn-throughs occur on the fireground and how this affects firefighters and the fire service industry. It also details pertinent conclusions from previous research on candidate materials.

2.1 Fireground Conditions

Modern day fireground environments have evolved over the past several decades, resulting in more intense fire conditions. Residential structures are becoming larger, allowing for increased fuel loads. Also, open floor plans, which lack passive containment, are becoming more common. Newly-engineered glued beams and synthetic building materials, which ignite more easily and promote faster flame spread, have replaced traditional wooden frames. These new beams are more unstable and unpredictable compared to dimensional lumber when under thermal attack. Household items are more abundant and are now constructed from more combustible synthetic materials. These new structure designs, building materials, and household commodities have led to rapid fire growth and intense fire conditions. As a result, modern structures are reaching flashover conditions at a rate eight times faster than structures built fifty years ago.

These decreased times to flashover and more unstable structures have led to changes in firefighting techniques but not in hose material. Firefighters are arriving at more unpredictable fire scenes and it is imperative that they have the tools appropriate to perform under such conditions. Firefighters' first line of defense, PPE, has developed continuously over the years. As fireground conditions change and develop a firefighter's second line of defense, the fire attack hose, should also develop, however, these hoses are still being manufactured from the same materials they were fifty years ago. Synthetic fiber and rubber hoses can still be found in fire departments' trucks and storage, but previous research has shown that these materials can burn-through. Therefore, this places firefighters at a higher risk of injury or death. According to *Analysis of Changing Residential Fire Dynamics* published by UL, residential fire room temperatures often reach temperatures of 400°C (750°F), and can even get as hot as 1200°C (2190°F). Popular fire hose materials, such as polyester, nylon 6,6, or a blend of each, have thermal failure temperatures of about 190°C (374°F) through 260°C (500°F) (Barolli et al, 2016). This discrepancy between fire hose thermal performance capabilities and the actual thermal environment encountered on the fireground has led to equipment failure. The evolution of the fireground gives insight on modern day conditions candidate materials will need to withstand.

2.2 Modern Day Fire Attack Hoses

Municipal fire attack hoses are designed in two different configurations: single or double jackets. Single jacket hoses are used for mostly forestry or industrial applications and they tend to be more lightweight. Double jacket industrial hoses tend to experience harsher conditions in structures and were more often seen when WPI MQP teams were collecting used hoses from U.S. Fire Departments. Hoses are constructed with an inner liner and outer jacket which are bonded together through the manufacturing process. Candidate materials discussed in this report are being investigated for use in the outer jacket of a fire attack hose.

Modern day municipal fire attack hoses are designed and manufactured according to NFPA 1961 *Standard on Fire Hose*. This standard explains the design requirements for several performance metrics such as flexibility, abrasion resistance, moisture resistance, pressure, and heat resistance. Municipal fire attack hoses are often rolled up for storage, dragged across rough surfaces, and exposed to high pressure, water, and heat. Due to these exposures, it is important that standards for fire attack hoses test hoses at the same rigor that they will be exposed to on the fireground. NFPA 1961 calls for testing significantly above the normal operating conditions for a majority of key properties. One example of this can be seen in pressure testing. The maximum operating pressure for a fire attack hose is 275 psi. Hoses are required to have a minimum design service pressure of 300 psi and all testing occurs at pressures of at least 1.5 times the design service pressure (450 psi). Some tests, like the burst test, require the hose to withstand at least 3 times the service pressure (900 psi).

In contrast to the rigorous pressure testing a fire attack hose must undergo, heat resistance testing is significantly less extensive. Although there are several modes of heat transfer that hoses will be exposed to, currently fire attack hose is solely tested for conduction and the level of conductive heat in this conduction test is below the level of conductive heat it will be subjected to on the fireground. NFPA 1961 only requires a conductive heat test to be performed. This test entails placing a solid steel block at 260°C on the hose for 60 seconds. As explained in the previous section, residential fire room temperatures can reach anywhere between 400°C and 1200°C. The two most common outer jacket materials currently used, nylon 6,6 and polyester, have melting points around 255°C and 195°C respectively and decompose near 255°C as stated in Table 1. It is clear that these two materials decompose around 255°C are well below the temperatures that they would be exposed to on the fireground.

Table 1: Material Properties of Nylon 6,6 and Polyester (*Handbook of Fire Resistant Textiles*, 2013)

Material	Melting Point (°C)	Decomposition Temperature (°C)	Max Service Temperature Short Term (°C)	Max Service Temperature Long Term (°C)
Nylon 6,6	255	254	180	80 - 95
Polyester	195	256	---	89.1

2.3 Research to Date on Candidate Materials

This project builds off of previous WPI research that concluded that current hose jacket materials do not withstand pre-flashover conditions. Previous research also initiated some testing of higher performing materials and proved that there are materials being manufactured that perform better in high heat environments than current materials, and certain candidate materials do not ignite until heat fluxes higher than those indicative of flashover. The previous project tested nylon 6,6, polyester, Kevlar, Nomex, PBI Max, PBI Kombat Flex, and Pyrovatex fr Cotton using a cone calorimeter. The radiative heat tests were performed for 15 minutes (900 seconds) at heat fluxes of 11.9 kW/m^2, 18 kW/m^2, and 24.2 kW/m^2. From their testing, they "determined that there are other materials currently being manufactured that are better suited for the high heat environment of the fireground than the current materials being used in fire hose jackets today" (Barolli et al, 2016). This work expands the research by testing more candidate materials and different heat fluxes.

3. Researching Candidate Materials

In order to identify existing materials currently used in other high heat applications that could potentially be used in the municipal fire hose industry, the team conducted research and gathered the following information. Nylon 6,6 and polyester, currently being used in outer jackets of municipal fire attack hoses, were selected for their properties such as rot and mold resistance, not their thermal resistance. However, there are other industries which utilize newly engineered fire-resistant and flame-retardant materials. These industries include personal protective equipment (PPE), thermal protection, home goods, and automotive/aerospace applications. These categories are further explained in Section 3.2.

3.1 Research Method

A literature review was conducted to uncover and investigate materials that may be better suited for use in the outer jacket of a fire attack hose than current materials. This literature review began with generating a list of keywords that could be used to search through technical databases. Some keywords that were used include:

- Fire Resistant Materials
- Fire Retardant Materials
- Fire Resistant Textiles
- Fire Retardant Textiles
- Fire Resistant Fibers
- Fire Retardant Fibers
- Heat Resistant Materials
- Heat Resistant Textiles
- Heat Resistant Fibers

These keywords were used to locate several trade journals, technical papers, and material handbooks. From these sources, a wide variety of fire and heat resistant materials were discovered. It was then possible to collect more information on each material using company websites and technical data sheets. A summary of the important aspects of a fire-resistant material as well as a brief description of each material found is provided in the following two sections. The team created a complex spreadsheet after obtaining the material names and company information. This can be found in Appendix A. These materials were then grouped by industry/application. Section 3.2 describes general characteristics and chemistry of fire-resistant and fire-retardant materials and Section 3.3 provides a brief description of each candidate material.

3.2 Fire-Resistant Materials

Many fire-resistant or fire-retardant materials are made of synthetic fibers. The Handbook of Fire Resistant Textiles states that the two most common classes of these fibers are the aramid family and the poly-benzazole family. The most common aramids are based on an aromatic amide meta-structure. This structure consists of amide linkages located in the meta position (substituents at the 1 and 3 position in the aromatic structure). Meta- aramids have excellent heat resistance and high temperature resistance. They also have moderate tenacity and low elasticity. Another type of aramid is the para-aramid in which the amide linkages are located in the para position (substituents at the 1 and 4 position in the aromatic structure). Para-aramids are typically the basis for protective clothing due to their high strength, non-flammability, and high temperature resistance. Blending meta-aramid fibers with para-aramid fibers can further improve their performance.

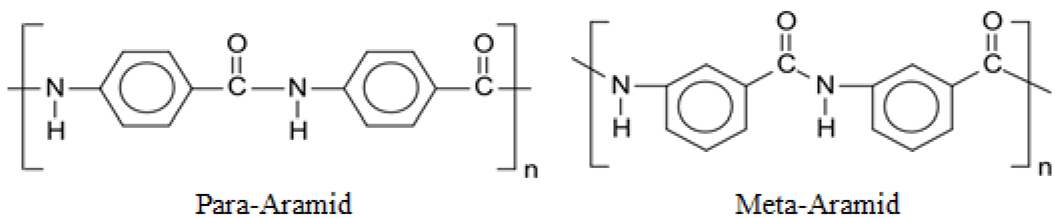


Figure 1: Types of Materials (*Handbook of Fire Resistant Textiles*, 2013)

The second family of fire-resistant fibers, poly-benzazoles, is also often found as the basis of protective clothing. These fabrics are puncture, tear, and rip resistant in addition to heat resistant. They also have excellent strength and elastic modulus. Poly-benzazole fibers are typically much more expensive than aramids so they are often blended with other materials to reduce cost. (*Handbook of Fire Resistant Textiles*, 2013)

3.3 Candidate Materials

The following paragraphs provide brief descriptions of the materials that were identified in the literature review described above. Candidate materials are used in multiple real world applications and they are presented here by their primary application. Further technical details for each material can be seen in Appendix A.

3.3.1 Personal Protective Equipment

The materials listed in this category have their primary application in PPE which consists of firefighter turnout gear such as jackets, pants, and gloves, as well as other thermal protective clothing.

Apyeil and ***Fenilon*** – These candidate materials were mentioned in the Handbook of Fire Resistant Textiles, which explains that these materials are used in the outer shell of firefighters' protective ensemble. They are a type of aramid fiber and Apyeil is produced by Unitika (*Handbook of Fire Resistant Textiles*, 2013).

Celiox – Celiox is produced by Celanese and is a semicarbon fiber used in the outer shell of firefighter protective ensembles (*Handbook of Fire Resistant Textiles*, 2013).

Gladiator – This material is also used in the outer shell of firefighter protective ensembles and is a blend of Kevlar and Basofil (*Handbook of Fire Resistant Textiles*, 2013).

Kermel – Kermel is a polyimide-amide fiber produced by Kermel. It is flexible and chemical resistant. In addition, it has very good resistance to abrasion. The primary applications of Kermel are in firefighter garments and industrial work wear ("Kermel Tech: High performance at the service of gas filtration," 2009).

Kombat Flex – Kombat Flex is a blend of PBI and Kevlar produced by TenCate. It is flexible and lightweight. In addition, Kombat Flex is abrasion and flame resistant ("TenCate Kombat Flex," 2014).

Kovenex – Kovenex is a heat and flame resistant fabric produced by Waubridge Specialty Fabrics. It is tear proof and is also certified by NFPA as a thermal barrier for firefighting gloves. Kovenex has applications in personal protective equipment like gloves and shirts, as well as in outdoor equipment and home/office furnishings ("Kovenex," N.D.).

Lenzing FR – Lenzing FR is a cellulose fiber produced from beech wood by the Lenzing Group. It protects from fires, radiant heat, electric arcs, and molten metals. The primary application for Lenzing FR is in protective clothing ("Lenzing FR," N.D.).

Nytox – Nytox is a thermo-oxidized polyacrylonitrile fiber produced in Russia by NPTs Uvikom. This material is fire resistant and chemically stable. It is also relatively inexpensive. The main application of Nytox is in protective clothing (Lavrent'eva, 2013).

P84 Aramid – P84 Aramid is a polyimide based fiber with an aromatic backbone. It is produced by Evonik Industries in Germany. This fiber is stable with most organic solvents but is sensitive to strong oxidizers. P84 Aramid meets all the typical requirements for common textile processing steps. It is commonly used in protective clothing, high temperature filtration, sealing materials for spacecraft, and heat insulation ("P84 Polyimide Fibres," N.D.).

Pavenex – Pavenex is produced by Waubridge Specialty Fabrics and is lightweight, durable, and abrasion resistant. It provides direct contact protection from arc flash, spark, extreme heat, and flame. It is a blend of carbon-based fibers which results in its flame-resistance. Pavenex is manufactured without many of the chemical treatments commonly used that may be potentially harmful ("Pavenex," 2010).

PBI Fiber – PBI Fiber is a fire resistant material produced by PBI Performance Products, Inc. PBI Fiber is lightweight and durable. It also has a high strength and good abrasion resistance. PBI Fiber has its applications in firefighter jackets and other personal protective equipment ("Gold," N.D.).

Teijinconex – Teijinconex is a meta-linked aromatic polyamide fiber that is produced by Teijin, a Japanese company. It does not stick to skin. Teijinconex is strong, light, soft, and self-lubricating. It is used primarily in clothing, filters, and copy cleaners. Company literature indicates that it is also used in hoses but the application of the hose was not stated ("Twaron - a versatile high-performance fiber," 2012).

Twaron – Twaron is a heat, cut, and chemical resistant material that is manufactured by Teijin. It has high strength as well as a high modulus. It also has high dimensional stability and is nonconductive. This material is available with a specialty finishes such as water blocking. Twaron can have some problems when exposed to sunlight. It is commonly used in protective clothing ("Twaron - a versatile high-performance fiber," 2012).

Zylon – Zylon is available in two grades: As Spun (AS) and High Modulus (HM) and is produced by Toyobo. It also comes in two types of fabrics: filament and spun yarn. Zylon is chemical, flame, and heat resistant, however it does experience some decrease in strength with exposure to light. Zylon is commonly used in firefighting garments, safety gloves, heat resistant garments, sports equipment, cable coverings, and speaker cones ("PBO Fiber Zylon," 2005).

3.3.2 Thermal Protection

Materials included in this category have applications in general thermal protection meaning that they are designed and manufactured to be used in environments where they would be exposed to a high heat flux. Examples of these include, but are not limited to, fire blankets, flame barriers, or protective fabrics.

Kynol Novoloid – Kynol Novoloid is a crosslinked phenolic resin that was developed in the United States and is now produced in Germany by Kynol GmbH. Kynol Novoloid has high flexibility and workability which is very good for production. It also has high flame and chemical resistance. In addition, it is a thermoset polymer which means that it will not melt or drip. Primary uses for Kynol Novoloid are in fire blankets, flame barriers, protective curtains, seat linings, and shoe soles ("GCI Gunei Chemical Industry," N.D.).

Millenia XT – Millenia XT is a para-aramid and PBO fiber blend produced by TenCate. It has good flame and abrasion resistance. In addition, Milenia XT has good durability, making it a viable option for thermal protection ("The Toughest Outer Shell Available in TenCate Millenia XT," 2016).

Nomex – Nomex is a heat and flame resistant material produced by DuPont USA. It is lightweight and has good chemical resistance for many chemical types. Nomex tends to lose some of its properties with prolonged exposure to sunlight ("Technical Guide for NOMEX Brand Fiber," 2001).

Ultra – Ultra is a Kevlar blend produced by TenCate in America. It has good flame and abrasion resistance. It also has good strength and is thermally stable. In addition, Ultra is competitively priced ("TenCate Ultra," 2014).

Technora – Technora is a para-aramid fiber produced by Teijin. It is made from copolymers. Technora has good fatigue resistance and long term stability. It also has good resistance to corrosion, heat, chemicals, and seawater ("Twaron - a versatile high-performance fiber," 2012).

3.3.3 Home Goods

This category includes items that are used in the manufacturing of commonly purchased items for the average household, including upholstery and mattresses.

Basofil **–** Basofil is an advanced technology melamine fiber produced by Basofil. It blends well with commodity fibers and other high temperature fibers to improve their properties. Basofil is competitively priced and has a low thermal conductivity. It has applications in filtration and can be found in bedding as well as in protective apparel ("Basofil Fibers, LLC," 2009).

Panox **–** Panox is an oxidized polyacrylonitrile fiber produced by SGL Group: The Carbon Company. This material is chemical resistant and a good electrical insulator. It is also thermally stabilized. Panox does not burn, melt, soften, or drip. Common applications for Panox include flame retardant mattresses, protective clothing, spark protection, fire blocking fabrics, and car disk brake pads ("SGL Group The Carbon Company," N.D.).

Protex – Protex is a modacrylic fiber manufactured by Kaneka Corporation and blends well with other fibers like cotton, rayon, or polyester. One important characteristic of Protex is that it can self-extinguish. Protex can be found in bedding, upholstery, drapery, carpet, faux fur, plush toys, and protective clothing ("Kaneka," 2016).

3.3.4 Automotive/Aerospace

Several materials have their primary application in the automotive or aerospace industries. These materials are used in high heat aspects of these vehicles, especially in brake systems.

Arselon – Arselon is a polyoxadiazole fiber produced by Heat Resistant Articles Production Company. This material is easy to produce and is manufactured in Russia for applications in special protective clothing, occupational safety and rescue equipment, aircraft and motor vehicle interiors, high temperature filter cloths, electrical insulation and brake composites. Arselon is stable under cyclic and static loads and has a high chemical and electrical resistance. At high temperatures it experiences low shrinkage. It is also wear resistant and non-abrasive. Arselon can experience some decrease in strength in the presence of water ("Arselon Withstanding Fiber," 2016).

Pyromex – Pyromex is an oxidized acrylonitrile fabric that is manufactured by Toho Tenax America, Inc. It is a non-flammable and heat resistant fabric In addition, Pyromex is non-melting and chemical resistant. It is also a good electrical insulator. Common uses for Pyromex are in protective clothing, fire-proof ceilings, nozzle sealing, heat insulation, and automobile/aerospace heat protection ("Pyromex," N.D.).

Pyron – Pyron is an oxidized acrylonitrile fiber. It is produced by Zoltek in America. Pyron is a thermoset, meaning it does not burn, melt, or drip. Instead, the material will char and self-extinguish. Pyron has its main application in aircraft brakes ("Technical Datasheet Pyron Continuous Tow," N.D.).

3.3.5 Other

Unlike the materials presented above that share common and widespread applications, this category includes candidate materials not related to those categories or to each other. Their applications are more unique and are being used in specialty markets.

Armatex SBN 13-602 Robotex **-** Armatex SBN 13-602 Robotex is a high temperature resistant material produced by Mid-Mountains Materials, Inc. It has a high strength and is chemical resistant. In addition it exhibits good abrasion resistance. Its primary applications are in welding, kiln seals, and expansion joints ("Mid-Mountain Materials Incorporated," 2016).

Grafil O – Grafil O is a polyacrylonitrile based carbon fiber produced by Mitsubishi Rayon Carbon Fiber & Composites, Inc. It has a high strength and has its primary application in tape production ("Mitsubishi Rayon Carbon Fiber & Composites," 2010).

Kevlar – Kevlar is produced by DuPont USA for use in ballistics and stab resistant body armor. It is lightweight and cut resistant. In addition, it has a good resistance to moisture ("Kevlar Aramid Fiber," N.D.).

M5 Fiber – M5 Fiber is produced by Magellan Systems International in partnership with DuPont for ballistics and armor systems in vehicles as well as flame and thermal protection. Ballistics testing was conducted on the material by the U.S. Army Natick Soldier Center (Body Armor News, 2005).

Nextel – Nextel is a ceramic oxide fiber produced in America by 3M Ceramic Textiles and Composites. This material has low shrinkage at high temperatures and has good chemical resistance.

Nextel also has a low thermal conductivity and provides good resistance to thermal shock ("Nextel Ceramic Textiles Technical Notebook," 2004).

Sigrafil O – Sigrafil O is an electrically conductive material produced by SGL Group: The Carbon Company. It is a free-flowing material that works well in the injection molding process. Common applications of this material are in adhesives, specialty paper, floorings, and cement reinforcements. Sigrafil O is often used to improve chemical resistance of materials ("Sigrafil Short Carbon Fibers," 2016).

Wool – Wool is available from many manufacturers. It is a good electrical insulator. On the other hand, it has poor chemical resistance against bases ("Wool," 2016).

4. Screening of Candidate Materials

Each of the 33 candidate materials identified from the literature was further screened to eliminate those that either had little information available, did not meet one or more of the performance metrics of fire hoses, or could not be ordered from companies. The criteria for the first round of elimination was whether or not the team could find company contact information for the material. M5 Fiber was eliminated in this initial round because Magellan Systems International was purchased by DuPont and DuPont stopped manufacturing the product in 2005. The companies for Arselon, Kynol Novoloid, Lenzing FR, and Nytox were unable to be contacted because they are located outside of the U.S. therefore these materials were eliminated from the candidate material list. Basofil was also excluded because it is no longer manufactured. All other candidate materials' company information was found and at the end of the first round, the team had a total of 27 candidate materials left.

The second round of elimination was based on material properties and the fire attack hose performance metrics discussed in Section 2.2. The properties investigated were tensile strength, elastic modulus, elongation at break, density, thermal conductivity, melting point, decomposition temperature, maximum service temperature, abrasion resistance, and moisture regain. These properties were chosen because they represented some aspect of the conditions that a fire hose would be exposed to as explained in NFPA 1961. Unfortunately, not all ten of these material properties could be found in the literature review for every candidate material. All but 11 of the 27 candidate materials had information about their heat resistance, specifically their melting point. These 11 materials were Armatex SBN 13-602 Robotex, Grafil O, Kermel, Kombat Flex, Lenzing FR, Millenia XT, Sigrafil O, Ultra, Zylon AS, and Zylon HM. After the second round of elimination, the team still had 16 materials for candidacy.

The third round of elimination was based on the given melting point of the candidate materials. Many of the candidate materials had no melting point so the team was able to eliminate materials that had melting points. Wool and Nextel were eliminated because they both have melting points lower than common fire temperatures. The team's list of candidacy now had a total of 14 materials.

Once this list of materials was compiled, the team eliminated the last round of candidate materials based on their availability from their respective manufacturing companies. The team began contacting companies to order samples but the companies that manufacture Kevlar, Nomex, P84 Aramid, Panox, Protex, and Technora were unable to provide samples of their materials. Because samples were not able to be obtained, these materials were excluded from the candidate material list as well. PBI Performance Products was able to provide two different PBI fibers, namely PBI Gold and PBI Matrix. Teijin was also able to provide two types of samples for Twaron. These were a knit Twaron and a woven Twaron. Two types of Pyron were able to be obtained as well. These were Pyron fabric and Pyron felt.

The final list of candidate materials for testing was as follows: PBI Gold, PBI Matrix, Twaron Knit, Twaron Woven, Teijinconex Neo, Kovenex, Pyron Fabric, Pyron Felt, Pavenex, and Pyromex, thus 10 of the 33 candidate materials were tested. The team also checked to be sure these 10 candidate materials spanned across the applications discussed in Section 3.3. The materials are from the personal protective equipment, thermal protection, and automotive/aerospace categories.

5. Development of a Test Method for Radiative Heat Testing of Materials

There are currently no standardized or accepted radiative heat tests required for fire attack hoses in the municipal fire hose industry. As discussed in Section 2.2, hoses are only subjected to a conductive heat transfer test before they are approved for use even though it is known that fire hoses are exposed to multiple sources of radiative heat on the fireground. An example is the radiative heat produced by objects in the burning compartment. Because no radiative heat test currently exists, the team needed to develop a procedure for radiative heat testing of candidate materials. The following sections describe the process of developing the test procedure. The selection of a radiative heat source is explained followed by an overview of the testing procedure and pass/fail criteria that were developed.

5.1 Identification of a Radiative Heat Source

Several requirements were considered in selecting a radiative heat source to be used as the basis of the test procedure. The heat source needed to be able to be set and maintained at a steady heat flux. It was necessary that heat flux could remain consistent between trials. The heat source also needed to be able to be used for small scale testing. Many candidate materials were only available as small samples so an apparatus that used a small sample size was desirable. The cone calorimeter, a widely known and accepted apparatus, was selected to meet these requirements.

The cone calorimeter was first developed after the importance of a reliable bench scale test method for heat release rate (HRR) was realized in the late 1970s and early 1980s and was the first apparatus that could accurately reflect the conditions of the fireground for testing. The cone calorimeter was first announced in a 1982 National Bureau of Standards (NBS) report (Society of Fire Protection Engineers, 2008).

The cone calorimeter is based on the oxygen consumption principle which states that in general the net heat of combustion of any organic material is directly proportional to the amount of oxygen consumed during combustion. Every kilogram of oxygen consumed releases approximately 13.1 MJ of heat. The cone calorimeter uses the oxygen combustion principle and a measurement of the oxygen depletion to provide the user with the heat release rate. The cone can also provide information on the heat flux, combustion products, and other parameters of combustion (Worcester Polytechnic Institute, 2015). Cone calorimeters rely on a sensing element that is sensitive to the partial pressure of oxygen in the cell and is designed for testing in ambient air.

The heating element for the cone calorimeter is an electrical radiant heater. This heater is located in the cone shaped element of the apparatus. The apparatus is depicted in the following schematic diagram. The cone shape was chosen because it allows for a hole in the middle of the heater to prevent a hot spot from developing in the center of the sample which is easy to verify with a heat flux gauge. The shape also prevents flames from the specimen from splashing onto the heater coil. The radiant heater is able to produce a uniform heat flux across the sample. In addition to the radiant heater, a spark plug is located above the center of the specimen to assist in ignition.

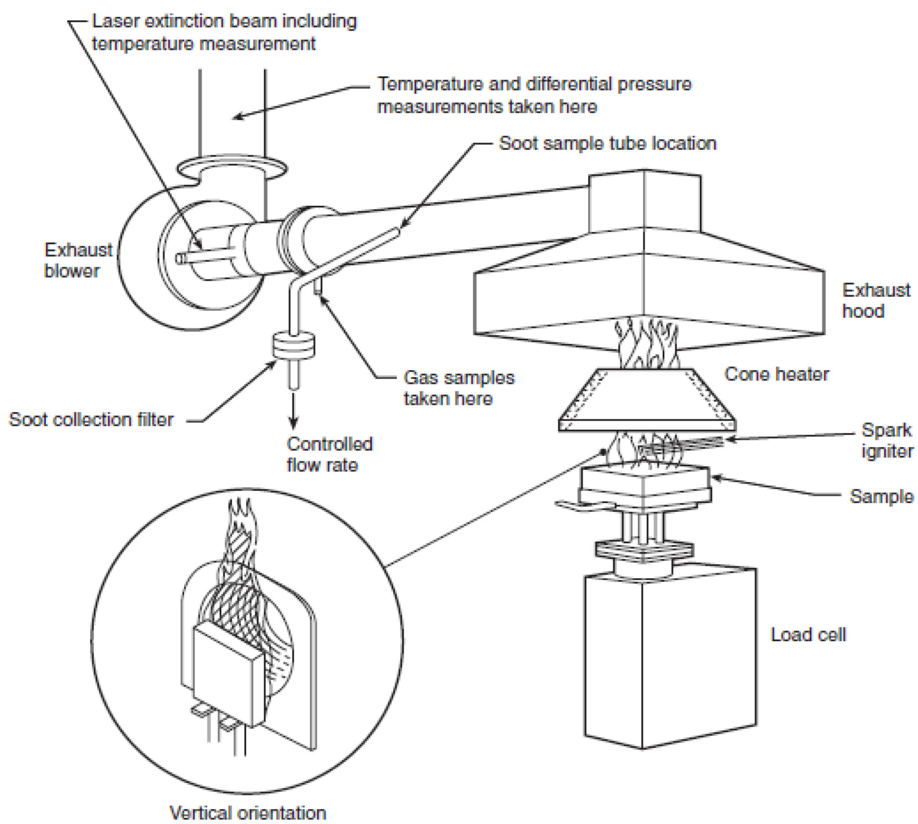


Figure 2: Cone Calorimeter Diagram

Several standards exist which should be followed to ensure proper use of the cone calorimeter. The most common of these standards are the Society of Fire Protection Engineers (SFPE) Handbook, ASTM E1354 - 15a Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter, ISO 5660 Reaction-to-fire tests - Heat release, smoke production, and mass loss rate, and the User's Guide for the Cone Calorimeter. These standards were used as a guideline while developing the methodology described in the following section. An elaboration on the history, use, design, and standards for the cone calorimeter can be found in Appendix B.

5.2 Testing Procedure for Candidate Materials

Once the cone calorimeter was selected as the radiative heat source, time to ignition and percent mass loss were selected as values measurable in a laboratory test that would provide an indication of the materials' performance on the fireground. Time to ignition was defined as the length of time it takes from the start of the test to the time a visible ember or flame is observed. Time to ignition is useful to determine each material's ability to withstand a set heat flux. Time to decomposition temperature was considered as a parameter; however decomposition temperatures were unavailable for the candidate materials and were unable to be measured in the limited timeframe of this project. Because decomposition causes mass loss, the overall percent mass loss was used instead. Temperature at the top and bottom surface of each sample was also recorded over the course of the experiment. If decomposition temperatures of the candidate materials are studied in the future, then time to decomposition can be determined from the raw data collected during the radiative heat tests shown in Appendix E. In addition to these quantitative measurements, qualitative observations such as burn-through, color changes, size changes, fiber changes, etc. were also recorded.

Before any testing could begin, samples needed to be prepared. All candidate materials were cut into 10 cm by 10 cm squares and weighed on a balance that had been previously calibrated. These masses were recorded for later use in calculating percent mass loss. Every material was able to be cut using kitchen shears. The samples were then wrapped with aluminum foil and two thermocouples were held in place between the foil and the sample with insulative cement. The cement ensured that thermocouples would not be able to shift during sample rig assembly or testing. A cardboard template was used to ensure that thermocouples were consistently placed in the same location for each test. The foil wrapped sample was then placed in a metal edge frame. Together, the foil and edge frame were used to prevent ignition and disproportionate burning at the sample edges as well as to contain any dripping during combustion. A fiberglass substrate was placed below each sample in the edge frame and a wire grid was placed on top. The wire grid was used to contain any swelling in the event that a material experienced intumescence. Two thermocouples were placed on top of the sample directly above the bottom thermocouples. Care was taken to make sure the thermocouples did not touch the wire grid as that would skew temperature readings.

To set the heat flux for the cone calorimeter, a calibration curve, shown in Appendix C, was used to estimate a temperature that corresponded to the desired heat flux. The cone was set to this temperature and allowed to stabilize before a heat flux gauge was used to confirm that the delivered heat flux corresponded to the desired heat flux. A trial and error method was used to set the cone to a temperature that provided the desired heat flux. Measuring the heat flux was crucial in ensuring that each material was exposed to the correct heat flux.

Once the sample rig was fully assembled and the heat flux was set, the sample was placed on the load cell for the calorimeter. The sample height was adjusted so that it sat 13 mm below the spark plug which was 13 mm below the heat source. This set-up ensured consistency across all trials of this study. Temperature recording and stop watches were started simultaneously with opening the shutter for the cone. Each sample was exposed to the radiative heat source until it was fully consumed or fifteen minutes (900 seconds) had elapsed, whichever occurred first. If a material extinguished after a period of ignition, the test continued so that it could be seen if the sample would reignite. At the end of the test, temperature recording was stopped and the shutters were closed. The sample was removed from the cone using protective gloves and allowed to cool under a nearby exhaust hood. The sample rig was disassembled and the sample was reweighed after it was cool. A step by step procedure can be found in Appendix D.

5.3 Pass/Fail Criteria

To pass the radiative heat test, the material needed to withstand the full 15 minute (900 second) exposure time with no ignition or observed burn-through. A burn-through is defined in this study as a hole formed in a material due to exposure to heat. Any material that ignited or burned through was considered to have failed the test. Percent mass loss was not considered in determining whether a material passed or failed because without additional testing it is not known how much percent mass loss can be accepted without altering other mechanical properties. Percent mass loss was, however, used to compare candidate materials to each other. Lower percent mass losses were characteristic of more desirable materials.

6. Testing of Candidate Materials

The team decided to test at three heat fluxes for this study, 20 kW/m^2, 30 kW/m^2, and 40 kW/m^2. The first heat flux, 20 kW/m^2 represents flashover conditions. The team hypothesized the candidate materials would withstand this vital fireground condition where current materials did not (Barolli, et al., 2016). The team chose the other two heat fluxes because 30 kW/m^2 is one and a half times flashover and 40 kW/m^2 is twice flashover conditions.

In order to provide an indicator of repeatability, each candidate material was tested twice at each of the three heat fluxes. The team wanted to ensure reproducibility of the results obtained through testing as well as explore how consistent the data points would be. The team completed all tests at a given heat flux before proceeding to the next heat flux. This helped to ensure that the heat flux remained consistent throughout testing. The heat flux was also checked every five trials during each testing period to further ensure that there had been no drift throughout the course of the experiment. It was necessary to ensure consistency and accuracy in the heat fluxes being used so care was taken to accurately measure them using a heat flux gauge.

Table 2: Completed Test Matrix

Material	20 kW/m^2	20 kW/m^2	30 kW/m^2	30 kW/m^2	40 kW/m^2	40 kW/m^2
PBI Gold	X	X	X	X	X	X
PBI Matrix	X	X	X	X	X	X
Twaron Knit	X	X	X	X	X	X
Twaron Weave	X	X	X	X	X	X
Teijinconex Neo	X	X	X	X	X	X
Kovenex	X	X	X	X	X	X
Pyron Fabric	X	X	X	X	X	X
Pyron Felt	X	X	X	X	X	X
Pavenex	X	X	X	X	X	X
Pyromex	X	X	X	X	X	X

Table 2 above shows the matrix of completed tests. Testing the materials in the order shown allowed for comparisons to be made early in the experimental process between materials that were expected to perform similarly. Materials were grouped by industry/application and were tested in the following order: personal protective equipment, thermal protection, and automotive/aerospace. This allowed materials that were likely to be the most promising candidates to be tested earlier in the experimental process. Each material's data was stored in a subfolder on the lab computer as well as on a flash drive for backup.

Throughout the testing process, observations for materials such as burn-through, color changes, and stability were recorded in addition to temperature, time to ignition, and percent mass loss as previously stated. Temperature profiles obtained during testing can be found in Appendix E.

7. Results and Discussion

The results of this study are presented below. As a reminder, the test procedure is discussed in Section 5.2 and the pass/fail criteria in Section 5.3. Time to ignition was defined as the time from initial exposure to when smoldering or flaming was observed. To pass the test the candidate material must have withstood the full 15 minute (900 seconds) exposure time with no ignition or burn-through. A burn-through is defined as a hole formed in a material due to exposure to heat.

Previous research on current materials has shown that polyester and nylon 6,6 fail at a heat flux at which pre-flashover occurs, shown in Table 3 below. The data presented in the following sections clearly demonstrates that there are candidate materials available with higher levels of heat resistance than what is currently used. These materials may be suitable for a next generation fire attack hose and should be evaluated for the full range of performance metrics such as abrasion, strength, etc. per NFPA Standard 1961.

Table 3: Current Material Performance (adapted from Barolli et. al., 2016)

Material	11.9 kW/m^2		18 kW/m^2	
	Decomposition	Ignition	Decomposition	Ignition
Polyester	Yes	No	Yes	Yes
Nylon 6,6	Yes	No	Yes	Yes

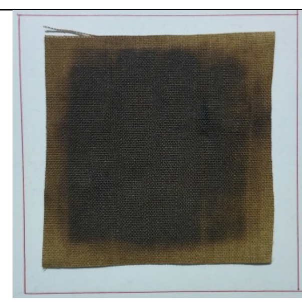
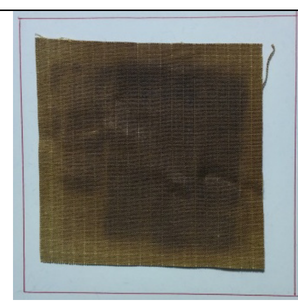
7.1 Heat Flux of 20 kW/m^2

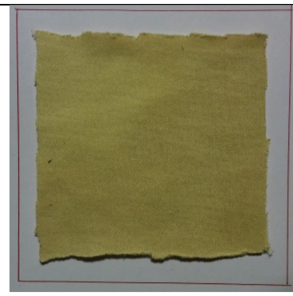
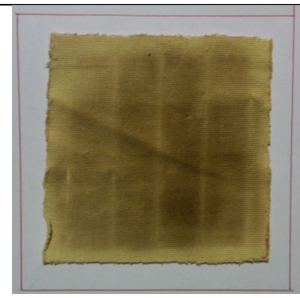
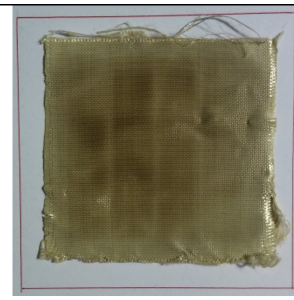
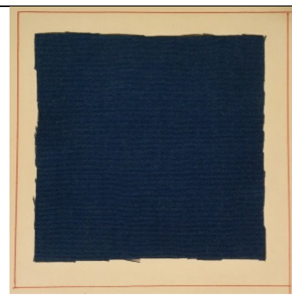
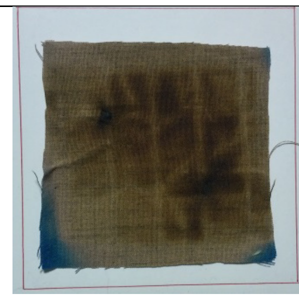
Every candidate material investigated in this project was able to pass the radiative heat test at a heat flux of 20 kW/m^2, a widely accepted value as an indicator of flashover (National Institute of Standards and Technology, 2010). This project has demonstrated that each of the ten candidate materials tested is able to withstand flashover conditions for a full 15 minute (900 seconds) exposure without burning through or igniting.

7.1.1 Observations

The team documented observations before and after each test for each candidate material. Although each material passed the tests performed at 20 kW/m^2, it is nonetheless important to observe changes the materials underwent. Trials were observed throughout the full time span of the test in order to document important visual observations. In addition, photographs were taken to document physical and chemical changes the team observed during the radiative heat tests, shown in Table 4 below. The team compared each material's before and after pictures to each other as well as comparing one material to another. The team observed that thinner materials underwent a drastic color change and decomposition patterns can be seen on the material. PBI Gold, PBI Matrix, Twaron Knit, and Twaron Weave all change to a darker color overall and browning is observed in the center of the samples from pyrolysis occurring. Teijinconex Neo underwent a significant change from a deep blue hue to a light yellow color with charring.

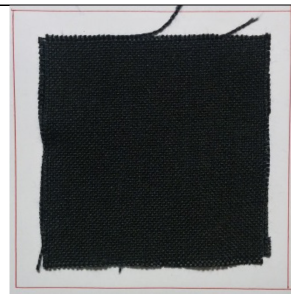
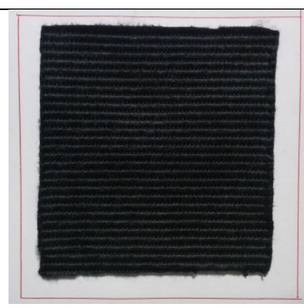
Table 4: Before and After Photos of Materials Passed at 20 kW/m^2

Material	Before	After
PBI Gold		
PBI Matrix		

Twaron Knit		
Twaron Weave		
Teijinconex Neo		

The thicker and felt-like materials, Kovenex, Pyron Felt, and Pavenex, became compressed and more brittle compared to samples that did not undergo testing. These materials were very fragile to handle when the tests were completed. Pyron Fabric and Pyromex both seem to have "shrunk" and their weaves look tighter but the materials do not appear to have melted. Individual fibers are still clearly visible. These pictures are shown in Table 5 below.

Table 5: Before and After Photos of Materials Passed at 20 kW/m^2

Material	Before	After
Kovenex		
Pyron Fabric		
Pyron Felt		
Pavenex		
Pyromex		

An impression of the metal grid placed on top of the samples during testing can be seen on all candidate materials except Pyron Fabric. All materials tested performed similarly in terms of ignition and burn-through at this heat flux. The other piece of data that was recorded in this investigation was percent mass loss.

7.1.2 Quantitative Measurements

Percent mass loss was used to provide a relative ranking of the effect of pyrolysis and decomposition on the candidate materials. Use of a percent mass loss (as opposed to amount of grams lost) was more meaningful because samples were initially of different weights and thicknesses. The team calculated the percent mass loss for each trial using Equation 1 below.

$$\%\, m_{loss} = \frac{(m_{before} - m_{after})}{m_{before}} * 100\% \tag{1}$$

m_{before} – the mass of the material sample before the test [grams]
m_{after} – the mass of the material sample after the test [grams]

The percent mass loss data was used to rank the candidate materials by the lowest to highest percent mass loss at a heat flux of 20 kW/m^2 presented in Table 6 below. Because the team performed two tests of each candidate material, the percent mass losses were averaged. Refer to Appendix F for the raw data of each trial performed.

Table 6: Data Recorded at 20 kW/m^2

Material	Burn-Through	Ave. Ignition Time (s)	Ave. Percent Mass Loss
Twaron Knit	No	No	1.48
Twaron Weave	No	No	2.62
PBI Matrix	No	No	5.39
Teijinconex Neo	No	No	7.32
PBI Gold	No	No	8.25
Pyromex	No	No	12.40
Pyron Felt	No	No	16.84
Pavenex	No	No	17.24
Pyron Fabric	No	No	17.97
Kovenex	No	No	27.52

At flashover conditions, these materials lost between about 1.5% up to almost 30% of their mass. Twaron Knit and Twaron Weave showed the lowest average percent mass losses, at 1.48% and 2.62% respectively. This indicates that at a heat flux of 20 kW/m^2, these two materials experienced the least amount of pyrolysis. Even though all the materials met the criteria for passing the test, some exhibited high amounts of percent mass loss. Kovenex exhibited the greatest percent mass loss at this heat flux. Its average percent mass loss was around 10% higher than the percent mass loss for the next two highest materials, Pyron Fabric and Pyromex.

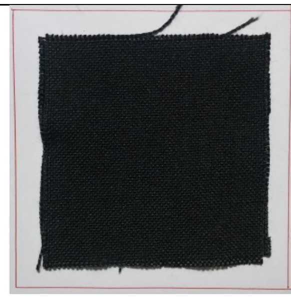
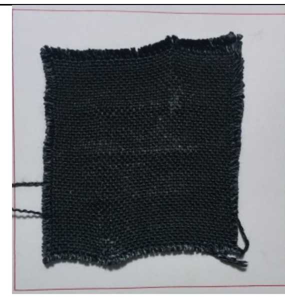
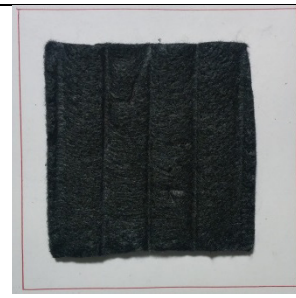
7.2 Heat Flux of 30 kW/m^2

When the heat flux was increased from 20 kW/m^2 to 30 kW/m^2 some materials began to fail according to the pass/fail criteria of this study. A heat flux of 30 kW/m^2 corresponds to one and a half times more than flashover conditions. The candidate materials that passed trials at this heat flux may be able to survive post-flashover conditions on the fireground.

7.2.1 Observations

The team documented more physical and chemical changes of the candidate materials at a heat flux of 30 kW/m^2 in comparison to the damages seen at heat fluxes of 20 kW/m^2. Four materials, Pyron Fabric, Pyron Felt, Pavenex, and Pyromex, were able to pass the radiative heat test at this heat flux. Table 7 below shows the before and after pictures of these materials. Pyron Fabric and Pyromex seem to have "shrunk" more significantly than they did at a heat flux of 20 kW/m^2, shown in Table 5. Pavenex and Pyron Felt are more compressed and brittle than they were after experiencing a heat flux of 20 kW/m^2.

Table 7: Before and After Photos of Candidate Materials that Passed at 30 kW/m²

Material	Before	After
Pyron Fabric		
Pyron Felt		
Pavenex		
Pyromex		

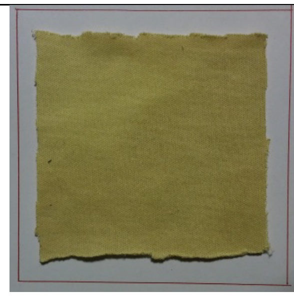
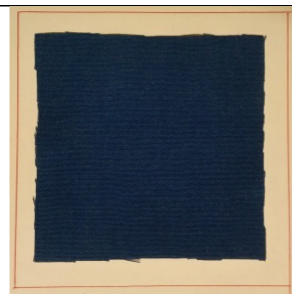
The team observed burn-throughs and smoldering occurring during the radiative tests for some materials at this heat flux, specifically PBI Gold, PBI Matrix, Twaron Knit, Twaron Weave, Teijinconex Neo, and Kovenex. Interestingly, a material did not have to ignite to result in a burn-through. PBI Gold, PBI Matrix, and Teijinconex Neo each experienced a burn-through without showing any signs of ignition.

Twaron Knit, Twaron Weave, and Kovenex each smoldered at this heat flux which resulted in burn-throughs.

The candidate materials that experienced a burn-through during the radiative test are shown in Table 8 below. When comparing these materials to each other, PBI Gold experienced a larger burn-through than PBI Matrix but Twaron Knit, Twaron Weave, and Teijinconex Neo all experienced even larger burn-throughs. All five of these materials reached a maximum surface temperature in a range of approximately 500°C - 600°C, as shown in Appendix E. When holding the samples up to a source of light, such as a fluorescent light, the weaves of PBI Gold, Twaron Knit, Twaron Weave, and Teijinconex Neo are more "spread out." The fibers in the weave can still be seen but due to pyrolysis they have decomposed and appear thinner. Kovenex performed similarly to Pavenex and Pyron Felt because it too became more compressed and brittle after undergoing the radiative heat test at 30 kW/m^2.

Table 8: Before and After Photos of Candidate Materials that Failed at 30 kW/m^2

Material	Before	After
PBI Gold		
PBI Matrix		

Twaron Knit		
Twaron Weave		
Teijinconex Neo		
Kovenex		

7.2.2 Quantitative Measurements

Every material experienced a greater average percent mass loss at 30 kW/m^2 when compared to 20 kW/m^2 as expected but percent mass loss did not increase by the same amount for each material. Variations in the chemical make-up and structure of each material could result in different heat resistance profiles. These material differences could cause the variations in percent mass loss. The average percent mass losses for each material at 30 kW/m^2 are shown in Table 9 below.

Table 9: Data Recorded at 30 kW/m^2

Material	Burn-Through	Ave. Ignition Time (s)	Ave. Percent Mass Loss
PBI Matrix	Yes	No	26.62
Twaron Knit	Yes	542	28.79
PBI Gold	Yes	No	29.31
Pyron Felt	No	No	33.85
Pavenex	No	No	34.39
Pyromex	No	No	37.77
Pyron Fabric	No	No	38.65
Teijinconex Neo	Yes	No	41.35
Twaron Weave	Yes	538	54.31
Kovenex	Yes	815	56.77

The percent mass loss data was again used to rank the materials in order of lowest to highest percent mass loss. The highest amount of percent mass lost at 20 kW/m^2 was within one percent of the lowest percent mass lost at 30 kW/m^2. Although PBI Matrix, Twaron Knit, and PBI Gold have the lowest average percent mass losses, they were not able to pass the radiative heat test due to burn-throughs. Pyron Fabric, Pyron Felt, Pavenex, and Pyromex all passed the radiative heat test and had very similar percent mass losses ranging from 33% - 40%. These were the next lowest percent mass losses after PBI Matrix, Twaron Knit, and PBI Gold. Similarly to the lower heat flux test, Kovenex again experienced the highest percent mass loss out of the ten candidate materials. It experienced 27.52% at 20 kW/m^2 and 56.77% at 30 kW/m^2. Twaron Weave showed a much larger percent mass loss at 30 kW/m^2 than it did at 20 kW/m^2, 54.31% and 2.62% respectively.

Table 9 also shows the average time to ignition the team recorded during trials of candidate materials that ignited. Twaron Knit, Twaron Weave, and Kovenex all experienced smoldering, as mentioned above. Twaron Knit and Twaron Weave both ignited at approximately 9 minutes, 542 seconds and 538 seconds, respectively. These two times are within 1% of each other while Kovenex experienced ignition starting at about 13.5 minutes (815 seconds). Even though Kovenex ignited approximately 4.5 minutes after Twaron Weave, Twaron Weave had a similar average percent mass loss to Kovenex.

7.3 Heat Flux of 40 kW/m^2

When subjected to a heat flux of 40 kW/m^2, seven materials failed according to the pass/fail criteria of this study. However, what is more important is that three materials actually withstood the full 15 minute (900 seconds) exposure. A heat flux of 40 kW/m^2 corresponds to twice the heat flux at the onset of flashover. This is more than double the heat flux existing materials were able to pass a radiative heat test.

7.3.1 Observations

At this heat flux most of the materials burned completely, except for the edges which were protected by the aluminum foil and edge frame. An example is shown below in Figure 3. After each test was performed at this heat flux, most of the samples were too delicate to remove from the sample holder without breaking them apart, even after they had fully cooled to room temperature. Six of the materials that failed at this heat flux failed due to ignition. Teijinconex Neo, however, did not ignite but instead disintegrated. Of the materials that ignited, two experienced flaming, Kovenex and Pyron Fabric, while the others exhibited smoldering. Three materials, Pyron Felt, Pavenex, and Pyromex, passed the radiative heat test at this high heat flux. These three remained intact and were easily removed from the sample holder. Pyron Felt and Pavenex again looked compressed and were very brittle. Pyromex looked as if its fibers had shrunk again.

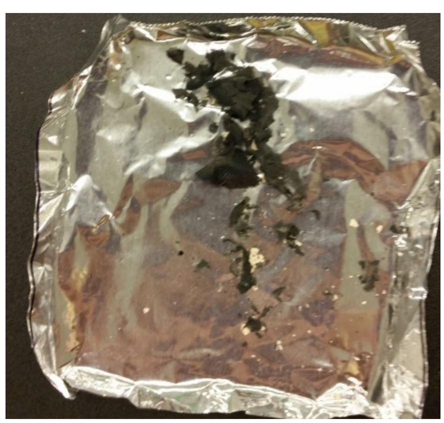


Figure 3: Example of Sample after Exposure to 40 kW/m^2

7.3.2 Quantitative Measurements

Average percent mass losses again increased as heat flux increased from 30 kW/m^2 to 40 kW/m^2 as expected. Percent mass losses at this heat flux are reported in Table 10 below. Many of the candidate materials completely decomposed, however, because sample edges were protected by aluminum foil and a frame, percent mass loss was never 100% for any candidate materials. Some samples had very small amounts of combustion products stuck to the foil. Other materials had such lightweight combustion products that upon removal from the cone calorimeter, ash could be seen floating into the air.

Table 10: Data Recorded at 40 kW/m^2

Material	Burn-Through	Ave. Ignition Time (s)	Ave. Percent Mass Loss
Pavenex	No	No	65.04
Pyron Felt	No	No	65.18
Pyromex	No	No	67.72
Pyron Fabric	Yes	21	77.90
Twaron Knit	Yes	126	79.92
PBI Gold	Yes	136	82.91
PBI Matrix	Yes	150	88.82
Teijinconex Neo	Yes	No	89.41
Kovenex	Yes	48	91.43
Twaron Weave	Yes	149	94.27

The ranking of candidate materials by average percent mass loss is very different than the ranking at 30 kW/m^2. The lowest percent mass loss at 40 kW/m^2 was higher than the highest percent mass loss at 30 kW/m^2. It is approximately 14% higher as the highest lost at 40 kW/m^2 is 65.04% while at 30 kW/m^2, the lowest is 56.77%. Pavenex, Pyron Felt, and Pyromex passed the test and experienced the lowest percent mass loss at this heat flux even though at 30 kW/m^2 they fell into the middle of the ranking ordered lowest to highest. Kovenex had a very high percent mass loss but it did not experience the highest percent mass loss as it did at a heat flux of 20 kW/m^2 and 30 kW/m^2, 27.52% and 56.77% respectively. Twaron Weave showed the highest average percent mass loss instead. Kovenex lost on average 91.43% while Twaron Weave lost 94.27%.

The team observed during the radiative heat tests whether or not the material completely decomposed before the end of the full 15 minute (900 seconds) exposure time. Both PBI Gold and PBI Matrix decomposed before the full 15 minutes (900 seconds) had elapsed at this heat flux and had completely burned through around the 12 minute (720 seconds) mark, shown in Appendix F. The other 8 candidate materials did not decompose fully before the full 15 minute (900 seconds) exposure time had elapsed.

Time to ignition data is also presented in Table 10 above. Four of the six candidate materials all ignited within a 2 to 2.5 minute (120 seconds to 150 seconds) time range. Pyron Fabric and Kovenex ignited outside of this range, both under 1 minute. Out of the candidate materials, Pyron Fabric ignited first but it experienced the lowest percent mass loss of those that ignited. Meanwhile, Kovenex ignited second but it lost the second highest percent of mass. When comparing ignition time at 40 kW/m^2 to 30 kW/m^2, all candidate materials that ignited did so much faster at the higher heat flux.

7.4 Summary of Results

Table 11 summarizes the results of this study and depicts which candidate materials passed and failed according to the criteria at each of the tested heat fluxes.

Table 11: Summary of Testing Results

Material	20 kW/m^2		30 kW/m^2		40 kW/m^2	
	Ignition	Burn-Through	Ignition	Burn-Through	Ignition	Burn-Through
PBI Gold	No	No	No	Yes	Yes†	Yes
PBI Matrix	No	No	No	Yes	Yes†	Yes
Twaron Knit	No	No	Yes†	Yes	Yes†	Yes
Twaron Weave	No	No	Yes†	Yes	Yes†	Yes
Teijinconex Neo	No	No	No	Yes	No	Yes
Kovenex	No	No	Yes†	Yes	Yes*	Yes
Pyron Fabric	No	No	No	No	Yes*	Yes
Pyron Felt	No	No	No	No	No	No
Pavenex	No	No	No	No	No	No
Pyromex	No	No	No	No	No	No

†Smoldering
*Ignition

As the table shows, more materials began to fail as heat flux increased leaving three materials able to pass every test: Pyron Felt, Pavenex, and Pyromex. Pavenex is from the PPE category while Pyron Felt and Pyromex are used in automotive/aerospace applications. Pyron Felt and Pavenex are both thick materials while Pyromex is a thinner material. Although all ten candidate materials are able to withstand the onset of flashover, only Pyron Felt, Pavenex, and Pyromex survived post-flashover conditions and significantly outperform current materials in the municipal fire attack hose industry.

8. Evaluation of Methodology

The following sections address challenges and inconsistencies that arose throughout the testing and analysis process.

8.1 Lessons Learned

Shake down tests were performed prior to data collection to ensure that the procedure would effectively meet the measurement goals. During the shake down testing, an unexpected temperature curve was found. This was traced to a draft in the room that was distorting the temperature profiles recorded by the thermocouples placed on top of the sample. To prevent this draft from disturbing the sample environment, the heat shield was lowered around the heat source and sample. In addition, it was found that the thermocouples on the bottom of the sample were moving during the sample rig assembly process. This was corrected by using extra thermally insulative cement around the portion of the thermocouple just below the bead. This allowed the thermocouples to stay in place without interfering with any temperature readings. In the original test procedure, only one thermocouple was placed on top of the sample and one thermocouple was placed on the bottom. To check that samples were being evenly heated, a second thermocouple was added to both the top and bottom of the sample in a different location. A heat flux gauge was also used to confirm that the cone calorimeter was providing an even heat flux to all areas of the sample. It was also ensured that thermocouple beads did not touch the metal grid placed on top of the sample and that all samples were evenly wrapped with aluminum foil.

8.2 Study Limitations

In analyzing the data it is necessary to point out that only two data points were recorded for each sample due to time constraints. Even though most of the results were reproducible within a certain degree, more trials would have helped the team identify any outliers in the data. Outliers are important to note because they may have affected the average values and standard deviations reported in Appendix F.. Additional confidence in the points that varied widely could be obtained by performing additional tests.

9. Conclusions and Recommendations

The following sections outline the team's conclusions as well as possibilities for further research on the subject.

9.1 Project Conclusions

This research project was able to show that there are several materials that have better resistance to a radiative heat flux than nylon 6,6 and polyester. All ten candidate materials were able to pass the radiative heat test at a heat flux of 20 kW/m^2 which exceeds the capabilities of current materials. Three candidate materials, Pyron Felt, Pavenex, and Pyromex, were the only materials able to pass the heat test at all three heat fluxes. These materials did not have the lowest average percent mass losses at 20 kW/m^2 but overall they performed well at every heat flux.

The radiative heat test procedure developed in this project was successful as a method for obtaining radiative heat data for candidate materials. Distinct differences in material performance at each heat flux were observed and can be easily seen in the recorded observations and photos that were previously presented. The data obtained throughout the course of this project is useful in considering what materials may be strong candidates for use as a next generation fire attack hose outer jacket.

9.2 Recommendations for Future Research

This project is just one step in the process of solving the fire attack hose burn-through problem. In order to solve this important issue it is necessary to continue research in several ways. First, it is recommended that additional tests on the materials analyzed in this report be performed to obtain additional data points and improve the confidence in the data presented here. It is also recommended that the search for new material candidates be expanded to locate any lighter weight materials. The ability to perform all tasks of a fire attack hose is important so it is recommended that the materials that performed well in the radiative heat test be subjected to other material property tests such as tensile testing, pressure testing, and abrasion resistance testing. Once materials have been selected as strong candidates for use as a new outer jacket, they should be combined with an inner liner material and tested. Heat resistant coatings should also be explored to further improve the heat resistance of potential materials. Lastly, it is suggested that a prototype of a next generation fire attack hose be developed.

As previously stated, the research presented here is just one step in the process of reaching a next generation fire attack hose design. Though it is just one step, it has been an important one. A research process for uncovering potential new materials was created and can be used as a stepping stone for any future researchers. In addition, a radiative heat test was developed to investigate the heat resistance of materials and a few materials have been proposed for further research. Combined with future studies, this project will be able to make the fireground safer for all those working to protect people.

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Appendices

The following appendices provide additional details regarding materials under consideration, temperature profiles obtained during testing, and resulting data tables.

Appendix A: Material Properties and Company Information

This Appendix contains all material property data used to determine which materials would be tested in this research project. The company for each material is also identified.

Table 12: Material Properties for Use in Narrowing Down Materials List

Material	Tensile Strength/ Tenacity	Elastic Modulus	Elongation (at break)	Density/ weight	Thermal Conductivity	Melting Point	Decomposition Temperature
Nylon 6,6	90 MPa	3450 MPa	>40%	1.14 g/cm3	0.28 W/mK	255 C	254 C
Polyester	23.6 MPa	478 MPa	436%	1.15 g/cm3	0.162 W/mK	195 C	256 C
Apyeil							
Armatex SBN 13-602 Robotex	100x50 lbs/in	11454x6917 (no units given)	90x73% (warp x weft)	441 g/m2			
Arselon	45 cN/tex		10-15%			none	500 C
Basofil	2.0-2.3 g/den		15-18%	1.4 g/cm3	0.028 W/mK	none	
Celiox							
Fenilon							
Gladiator							
Grafil O	308 ksi x 10 ksi (0x90)	19.89 msi x 1.35 msi		1.80 g/cm3			
Kermel	650 N	250 cN/tex	35%		low		>450 C
Kevlar	2920 MPa	70500 MPa	3.60%	1.44 g/cm3	0.04 W/mK	none	427-482 C
Kombat Flex	~1200 N			235 g/m2			
Kovenex							
Kynol Novoloid	15 cN/tex	3500 N/mm2	10-60%		0.0002 W/mK	none	gradual/time
Lenzing FR							

M5 Fiber								
Millenia XT	~2500 N			235 g/m2				
Nextel	1700 MPa	150000MPa	low	2.70 g/cm3	~0.11 W/mC	1800 C		
Nomex	5 g/den	94 g/den.	30.50%	1.38 g/cm3	0.25 W/mK	none (also no drip)		
Nytox								
P84 Aramid	650 N	"low"	30%	1.41 g/cm3	0.001 W/mK	none	450 C
Panox	220 MPa		22%	1.39 g/cm3	low	none		
PBI Fiber	2.4 dN/tex (320 MPa)	40 dN/tex (5100 MPa)	27%	1.4 g/cm3	0.038 W/mK	none	>700 C
Protex						none		
Pyromex	1.6 cN/dtex		15%	1.41 g/cm3		none		
Pyron	240-300 MPa		22-28%	1.37 g/cm3		none		
Sigrafil O	4000 MPa	240000 MPa	1.70%	1.80 g/cm3				
Technora	3400 MPa	74000 MPa	4.50%	1.39 g/cm3		none	500 C
Teijinconex	620-690 MPa	--	35-45%	1.38 g/cm3		none	400 C
Twaron	2400-3600 MPa	60000-120000 MPa	2.2-4.4%	1.44-1.45 g/cm3		none	500 C
Ultra	1300-1900 N			255 g/m2				
Wool	125-200 MPa		20-40%			570 C		
Zylon AS (as spun)	5800 MPa	180000 MPa	3.5%	1.54 g/cm3			650 C
Zylon HM (high modulus)	5800 MPa	270000 MPa	2.5%	1.56 g/cm3			650 C

Material	Short Term Max Service Temp	Long Term Max Service Temp	Abrasion Resistance	Moisture Regain	Additional Notes	Uses
Nylon 6,6	180C	80-95 C	yes	4%		
Polyester	--	89.1 C	some resistance	0.40%	Average values used	
Apyeil						
Armatex SBN 13-602 Robotex		260 C (fabric) 232 C (coating)	good		high temperature resistant, high strength, chemical resistant	applications for welding, kiln seals, expansion joints
Arselon	400 C	250 C	wear resistant, non-abrasive	not mentioned	stable under cyclic load and static load, high chemical resistance, low shrinkage under high temperatures, high electrical resistance, some strength decrease in presence of water, polyoxadiazole fibers, easy to produce	special protective clothing, occupational safety and rescue equipment, aircraft and motor vehicle interiors, high temperature filter cloths, electrical insulation, brake composites
Basofil	260-370 C	190 C	not mentioned	5%	advances technology melamine fiber, blends with commodity fibers/high temperature fibers, competitively priced, low thermal conductivity	filtration, bedding, protective apparel
Celiox						
Fenilon						
Gladiator						
Grafil O					carbon fiber, PAN based, high strength	tape production
Kermel	240 C	220 C	very good	not mentioned	1.1-2.2 dtex, 80-120 mm diameter, chemical resistance, polyimide-amide	firefighter garments, industrial work wear

					fibers, flexible	
Kevlar	not given	149-177 C	not mentioned	4-8% (good resistance)	Lightweight, cut-resistant	ballistics and stab resistant body armor
Kombat Flex			2500 cycles - good	<2%	good flame resistance, lightweight, flexible, abrasion resistant, blend of PBI and Kevlar	
Kovenex				water repellant	heat-resistant, flame-resistant, tear-proof, certified by NFPA as thermal barrier for firefighting gloves	gloves and shirts PPE, home and office furnishings, outdoor equipment
Kynol Novoloid	1000 C	150 C	not mentioned	<6%	high flexibility and workability (low modulus) , high flame and chemical resistance, crosslinked phenolic resin, thermoset, developed in the US, produced in Japan	fire blankets, flame barriers, protective curtains, seat linings, shoe soles
Lenzing FR					cellulose fiber produced from beechwood, protects from fires, radiant heat, electric arcs, molten metals, flash fires	protective clothing
M5 Fiber						
Millenia XT			2500 cylces - good	<1%	good flame resistance, durable, abrasion resistant, para-aramid & PBO combination	

Nextel		1204 C	some resistance	absorb very little moisture	low shriknage at high temperatures, good chemical ersistance, low thermal conductivity, thermal shock resistance, ceramic oxide fibers	
Nomex	fire fighter gear is good for many years	204 C	good	4% (good resistance to moisture)	chemical resistance for many chemicals, not good with prolonged exposure to sunlight, lightwieght, heat resistant, flame resistant	firefighter, military personnel, police officers, auto racing teams, industrial workers PPE
Nytox					Thermo-oxidized PAN, fire resistant, chemically stable, inexpensive, withstands open fire	protective clothing
P84 Aramid	260 C		not mentioned	3%	stable with most organic solvents, sensitive to strong oxidizers, composed of aromatic backbone units only, polyimide based, fibers meet the requirements for all common textile processing steps	filtration, protective clothing, sealing materials for space craft, heat insulation
Panox	1000 C		not mentioned	10%	Oxidized thermally stabilized polyacrylic nitrile (PAN) fiber, does not burn, melt, soften, or drip, chemically resistant, good electrical insulator	protective clothing, spark protection, fire blocking fabrics, flame retardant mattresses, car disk brake pads
PBI Fiber			not mentioned	15%	fire resistant	firefighter jackets and PPE
Protex					mixes with other fibers like cotton, rayon, polyester, self-extinguishes	protective clothing, bedding, upholstery, drapery, carpet, faux fur, plush toys

Pyromex				16%	oxidized PAN fiber, non-flammable, non-melting, heat, chemical resistant, good electrical insulator	protective clothing, fire-proof ceilings, nozzle sealing, heat insulation, auto/aero heat protection
Pyron			not mentioned		oxidized PAN fiber, does not burn, melt or drip, chars and self-extinguishes	aircraft brakes
Sigrafil O					electrically conductive	
Technora			not mentioned	1.90%	para-aramid fiber made from copolymers, good fatigue resistance, long term dimensional stability, resistance to corrosion, heat, chemicals, and seawater	
Teijinconex			yes	5-5.5%	meta-linked aromatic polyamide fiber, does not stick to skin, strong, light, soft, self-lubricating	clothing, filters, copy cleaners, hoses
Twaron			not mentioned	3.2-5%	some problems in sunlight, water blocking/other special finishes available, high strength, high modulus, high dimensional stability, heat, cut and chemical resistant, nonconductive	
Ultra			5000 cycles - good	<1%	good flame resistance, Kevlar blend, competitive cost, abrasion resistance, thermal stability, good strength	

Wool		400 C		16-18%	good electricity insulator, poor resistance against bases	
Zylon AS (as spun)			much lower than nylon, polyester	2%	strength decreases with exposure to light, chemical resistant, flame resistant, heat resistant, flame resistant, 2 types of woven fabrics: filament and spun yarn	firefighting garments, safety gloves, heat resistant garments, sports equipment, cable coverings, speaker cones
Zylon HM (high modulus)			much lower than nylon, polyester	0.60%	strength decreases with exposure to light, chemical resistant, flame resistant, heat resistant, flame resistant, 2 types of woven fabrics: filament and spun yarn	firefighting garments, safety gloves, heat resistant garments, sports equipment, cable coverings, speaker cones

Table 13: Materials and Companies

Material	Company
Apyeil	Unitika
Armatex SBN 13-602 Robotex	Mid-Mountains Materials, Inc.
Arselon	Heat Resistant Articles Production Co. (Russia)
Basofil	Basofil
Celiox	Celanese
Fenilon	- USSR
Gladiator	
Grafil O	Mitsubishi Rayon Carbon Fiber & Composites
Kermel	Kermel
Kevlar	DuPont USA
Kombat Flex	TenCate
Kovenex	Waubridge Specialty Fabrics
Kynol Novoloid	Kynol - Germany
Lenzing FR	Lenzing Group
M5 Fiber	
Millenia XT	TenCate
Nextel	3M Ceramic Textiles and Composites
Nomex	DuPont USA
Nytox	NPTs Uvikom - Russia
P84 Aramid	Evonik Industries - Germany
Panox	SGL Group: The Carbon Company
PBI Fiber	PBI Performance Products, Inc.
Protex	Kaneka Corporation- Osaka, Japan
Pyromex	Toho Tenax America, Inc.
Pyron	Zoltek
Sigrafil O	SGL Group: The Carbon Company
Technora	Teijin
Teijinconex	Teijin
Twaron	Teijin
Ultra	TenCate
Wool	
Zylon AS (as spun)	Toyobo
Zylon HM (high modulus)	Toyobo

Appendix B: The Cone Calorimeter

The cone calorimeter was the main testing apparatus the team used to analyze the potential materials for use in a next generation fire attack hose. The following sections provide information on this apparatus including its history and uses, design, and standards for operation.

History and Uses

The cone calorimeter was first developed after the importance of a reliable bench scale test method for heat release rate (HRR) was realized in the late 1970s and early 1980s. Several devices were already in existence at that time to try to measure HRR but had two main problems. These devices were often difficult to operate or install and had significant errors associated with their measurements. They did not accurately reflect the conditions of the fireground in testing. The cone calorimeter was first announced in a 1982 National Bureau of Standards (NBS) report.

The cone calorimeter is based on the oxygen consumption principle which was just discovered as the cone calorimeter was being developed. The basic principle has not changed since but there have been many additions and improvements to the design. The modern cone calorimeter barely contains any parts identical to the original apparatus. Two of the most important additions to the apparatus have been the ability to measure smoke optically and to measure soot yield gravimetrically. These additions were first reported in 1987. The cone calorimeter has revolutionized fire testing and is considered to be a good representation of actual fire conditions.

The earliest application of the cone calorimeter was in the polymer industry where it replaced a simple Bunsen burner test. From there, the applications of the cone calorimeter have grown to include providing data for cutting edge fire models, providing data for predicting real-scale fire behavior, rank ordering materials according to their performance, and pass/fail testing products to a specific criterion level. The main users of the cone calorimeter include manufacturers, government laboratories, independent testing laboratories, and universities. As the cone calorimeter continues to grow and develop, its uses will become even more widespread.

Design

The cone calorimeter has a very unique design which allows it to accurately simulate fireground conditions. It is designed to operate using only oxygen consumption as its measurement principle. Although manufacturers may use different measuring schemes, they all rely on the basic principle of a sensing element that is sensitive to the partial pressure of oxygen in the cell. Additional gas analyzers other than oxygen may be present as well to provide more extensive data. The cone calorimeter can achieve high irradiance with an immeasurably small convective heating component, especially when used in the horizontal orientation. The horizontal sample orientation (where the sample is face up with the heating element above) is the standard operating orientation. The machine can also be operated with a vertical sample orientation for special testing. The cone calorimeter is designed for testing in ambient air.

The heating element for the cone calorimeter is an electrical radiant heater. This heater is located in the cone shaped element of the apparatus. The cone shape was chosen for two reasons. First, this shape allows for a hole in the middle of the heater to prevent a hot spot from developing in the center of the sample. Second, it prevents flames from the specimen from splashing onto the heater coil. The radiant heater is able to produce a uniform heat flux through the sample. Deviations in heat flux over the thickness of the specimen are small enough that they may be neglected. In addition to the radiant heater, a spark plug is located 13 mm above the center of the specimen to assist in ignition. The calorimeter also has a load cell on which the sample is placed to determine mass changes over the course of the test. Lastly, one important aspect of the cone is the smoke measuring system. It consists of a helium-neon laser and quasi-dual beam arrangement to take measurements of the smoke.

The specimen for testing in the cone calorimeter has to meet specific requirements. First, it must have dimensions of 10 cm by 10 cm. In addition it must be between 6 mm and 50 mm thick. Thicknesses greater than 50 mm are considered thermally thick and are not necessary to test. A substrate should also be used below samples, especially in the case of thin specimens. Specimens should typically be wrapped in aluminum foil to limit dripping as the combust. In addition to the aluminum foil, a stainless steel edge frame is used to prevent ignition at the sample edges and disproportionate burning at the edges. Lastly, some samples may experience intumescence. Intumescence is the swelling of a material upon heating. A wire grid can be placed on a specimen to contain the swelling.

Standards

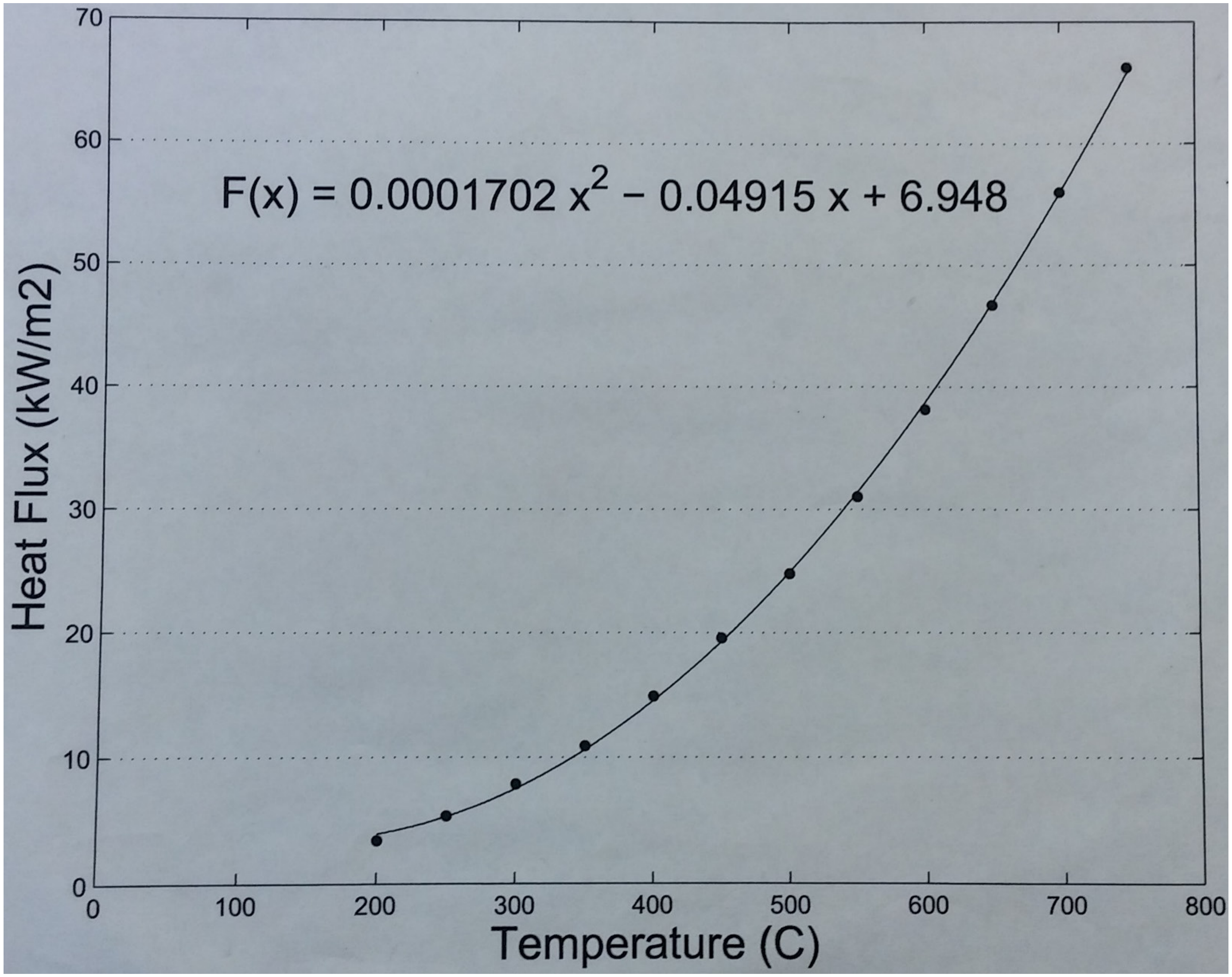
Several standards exist which should be followed to ensure proper use of the cone calorimeter. The most common of these standards are the Society of Fire Protection Engineers (SFPE) Handbook, ASTM E1354 - 15a Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using and Oxygen Consumption Calorimeter, ISO 5660 Reaction-to-fire tests - Heat release, smoke production, and mass loss rate, and the User's Guide for the Cone Calorimeter.

The SFPE Handbook provides a detailed explanation of the apparatus along with the reasoning behind certain design decisions. It also explains the standard specimen design and configuration. The SFPE Handbook provides a complete explanation of the capabilities of the cone calorimeter while referencing the other three standards for specific operating procedures.

ASTM E1354 - 15a begins by defining important terminology for understanding the operation of the cone calorimeter and analyzing the data. It also explains the significance and applications of the test method. This standard describes the apparatus to be used as well as its hazards. It also provides a detailed test procedure outlining every step from sample preparation to calibration to the test method. Necessary calculations and data to be reported are also summarized.

ISO 5660 is very similar to ASTM E1354 and consists of the same sections. The User's Guide for the Cone Calorimeter is also very similar to both ISO 5660 and ASTM E1354. This guide is NBS Special Publication 745. It focuses on the test procedure but places greater emphasis on calibration, maintenance, and troubleshooting of the cone calorimeter.

Appendix C: Cone Calorimeter Calibration Curve



Appendix D: Step By Step Test Procedure for Candidate Materials

Sample Preparation

1. Gather material to be tested and equipment needed.
2. Ensure equipment is thoroughly cleaned.
3. Using a 10cm X 10cm stencil, cut the material.
4. After cutting, ensure there are no loose ends or fibers that may skew data results.
5. Calibrate the scale using the calibration weights. Weigh the sample.
6. Place four thermocouples on the specimen, two on the top face to the upper right and the bottom left of the center and two on the bottom face directly below the top thermocouples. Ensure that the bottom thermocouples will not lift off of the specimen using a small amount of thermally insulated cement.
7. Wrap material sample with aluminum foil on the bottom and onto the edges of the material sample to prevent edge burning. Be sure that the shinier side is toward the specimen.
8. Place a retaining grid on top of the sample.
9. Place sample or sample and grid into loading block.

Start Up

1. Log onto computer and open calibration curves and software programs.
2. Turn on cone calorimeter machine.
3. Turn on cooling water flow to the heat flux gauge.
4. Turn on ventilation fan of the cone calorimeter.
5. Set temperature that corresponds to the desired heat flux from the calibration curve. The calibration curve will be generated weekly to ensure there are no changes in testing conditions.
6. Ensure shutters are closed and igniter is not on.
7. Once the calorimeter has reached an equilibrium state, measure the given heat flux using the heat flux gauge.

8. Change the temperature of the cone calorimeter if the required heat flux is not set.
9. Repeat steps 7 and 8 as needed.

Testing Procedure

1. Ensure thermocouple data is being read and recorded by the software programs.
2. Place sample block onto load and adjust the height. Ensure 1.3 cm of space will be between the radiant heat source and igniter. Ensure 1.3 cm of space will be between the sample and igniter.
3. Open the shutters of the cone calorimeter and simultaneously start timer and move igniter into position.
4. Observe sample material and record the following data.
    a. Time to Ignition
    b. Percent Mass Loss
5. Repeat testing procedure for heat fluxes of 20, 30, and 40 kW/m^2 for each sample material.
6. Each material must be run twice at each heat flux. Ensure data is consistent. If data is not consistent, repeat the test another two times.
7. Test duration will be 900 seconds for each test
8. After a sample has been tested. Remove the sample and block from the load and place under hood using tongs. Dissemble sample and sample block and allow to cool under the hood.
9. Reweigh the sample.
10. Repeat procedure for each test.

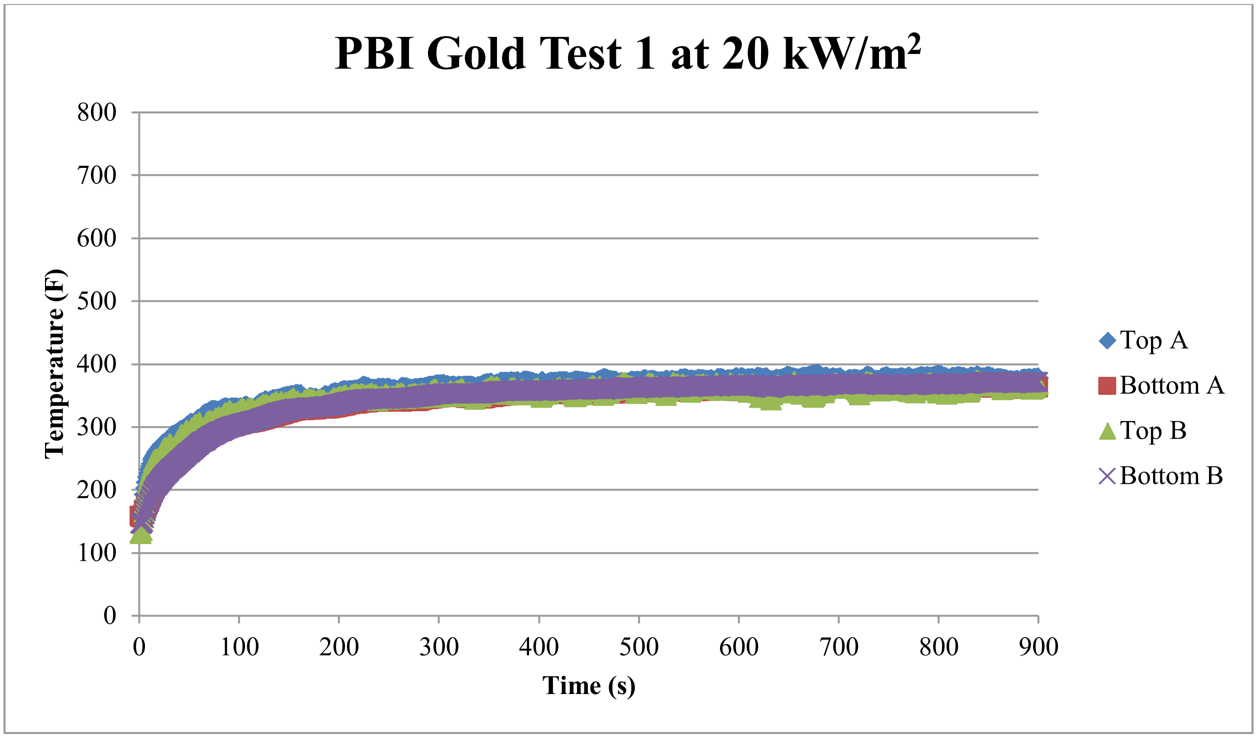
Shut Down

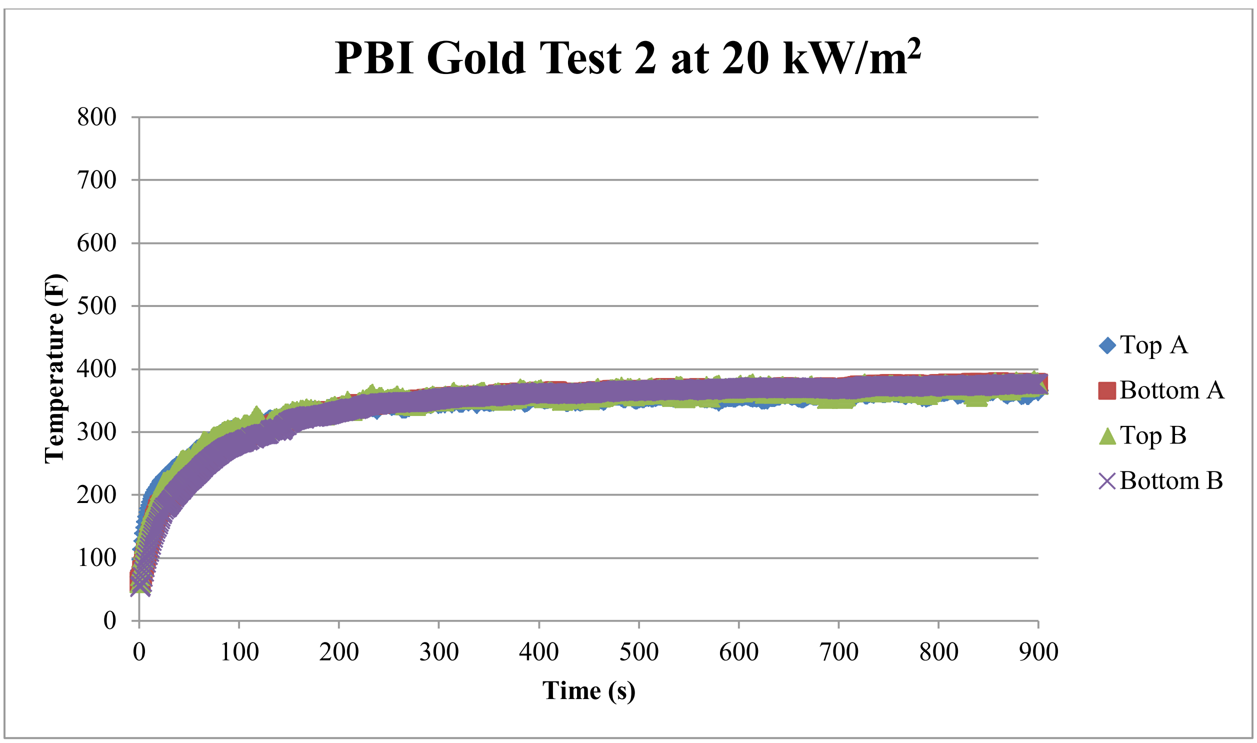
1. Turn temperature of cone calorimeter down and wait approximately 5 minutes.
2. Turn cone calorimeter heat source off but leave on cooling water flow.
3. After approximately 5 minutes, turn off cone calorimeter completely.
4. Turn off cooling water flow.

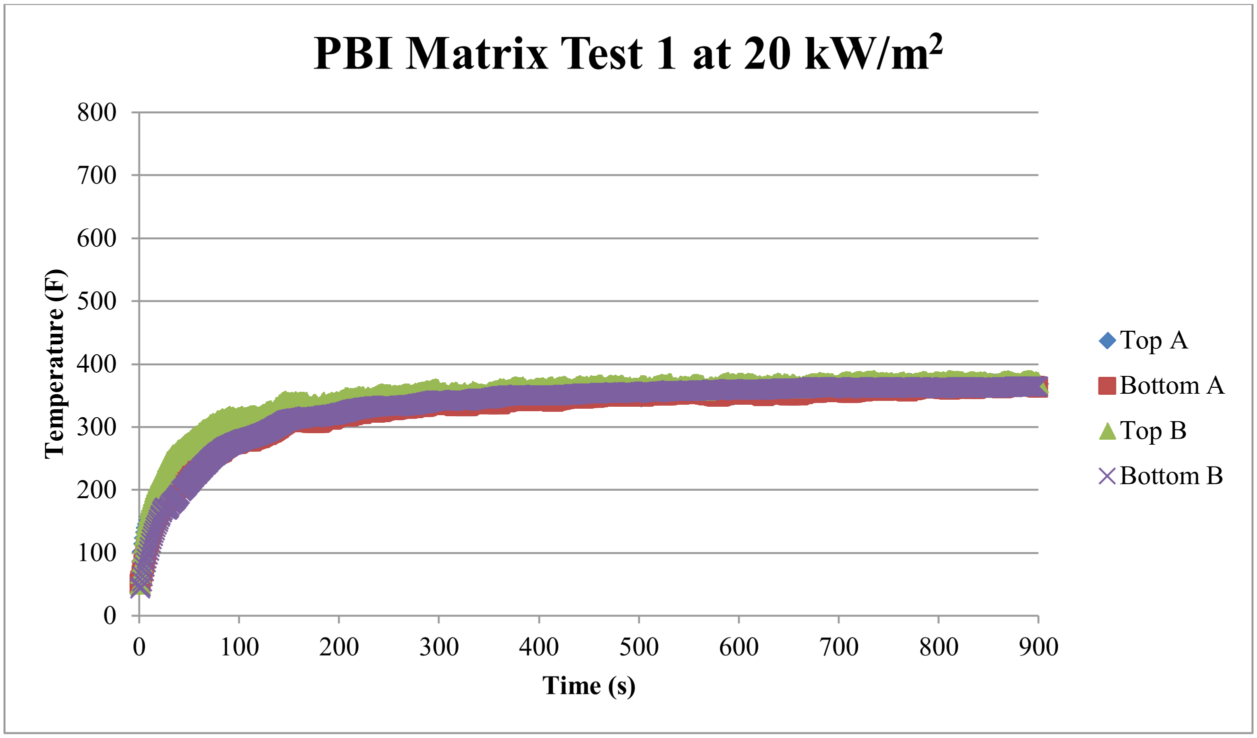
Appendix E: Temperature Profiles Obtained During Testing

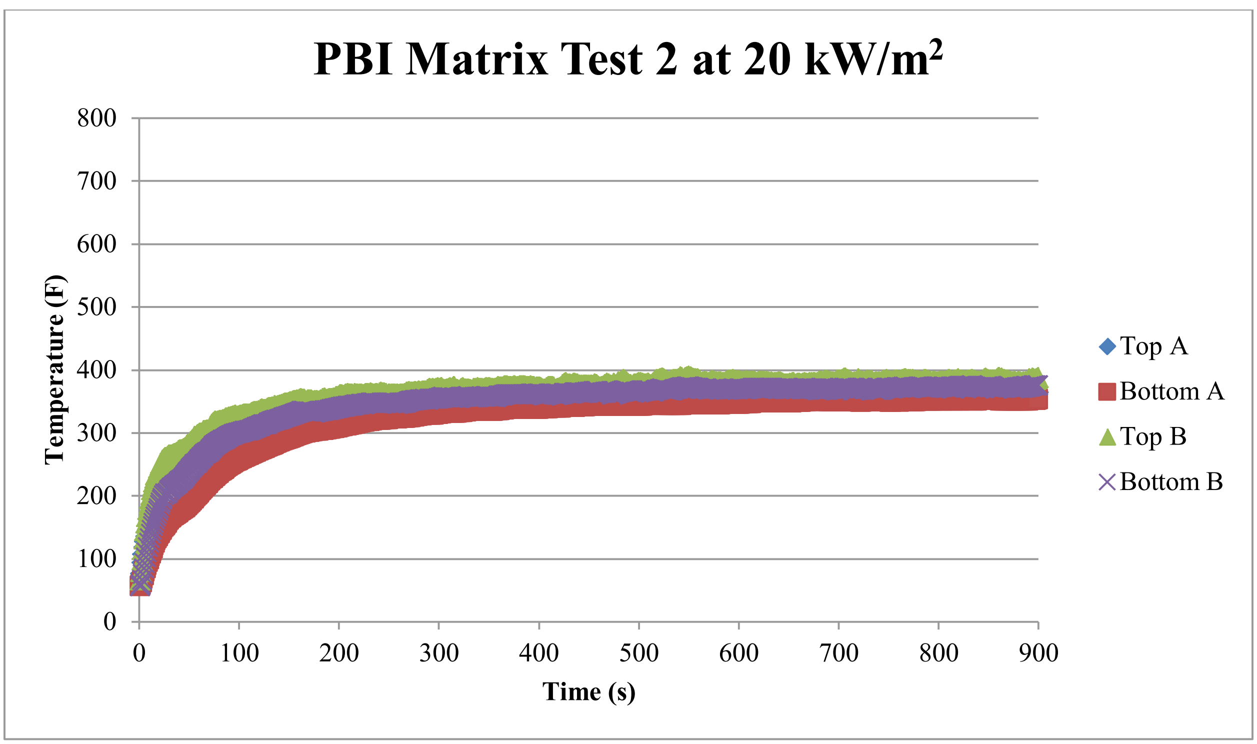
Temperature profiles for each test are included in this Appendix. For ease of navigation, they are divided into sections by heat flux. These profiles were intended to be used in conjunction with decomposition temperature data. The decomposition temperature for each material can be marked on its respective graph which can then be used to determine the time to decomposition. Time to decomposition is another parameter useful in determining a material's ability to withstand a specified heat flux. These temperature profiles can also be used to determine the maximum temperature each material reached when exposed to a specified heat flux and the time it took for them to reach this maximum. These graphs are presented on the following pages. Each of the two trial tests are on the same page.

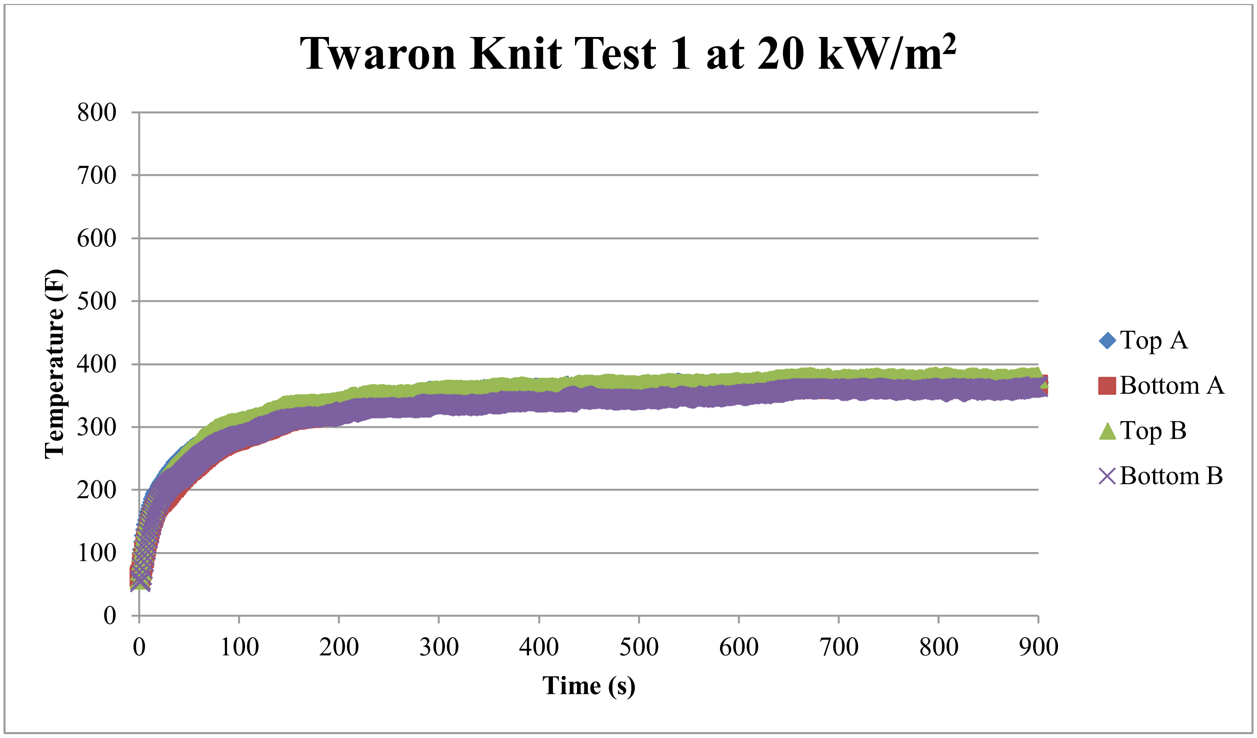
Heat Flux of 20 kW/m^2



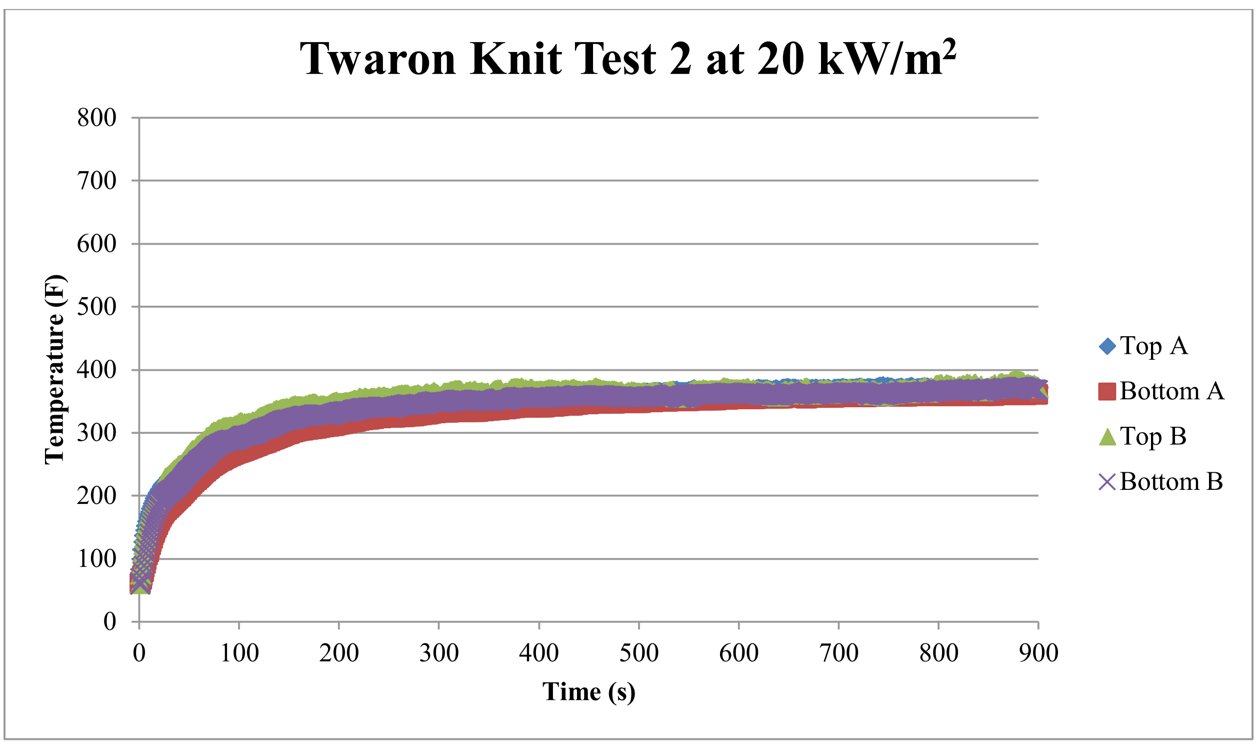



PBI Matrix Test 1 at 20 kW/m2
Temperature (F)
0
100
200
300
400
500
600
700
800
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

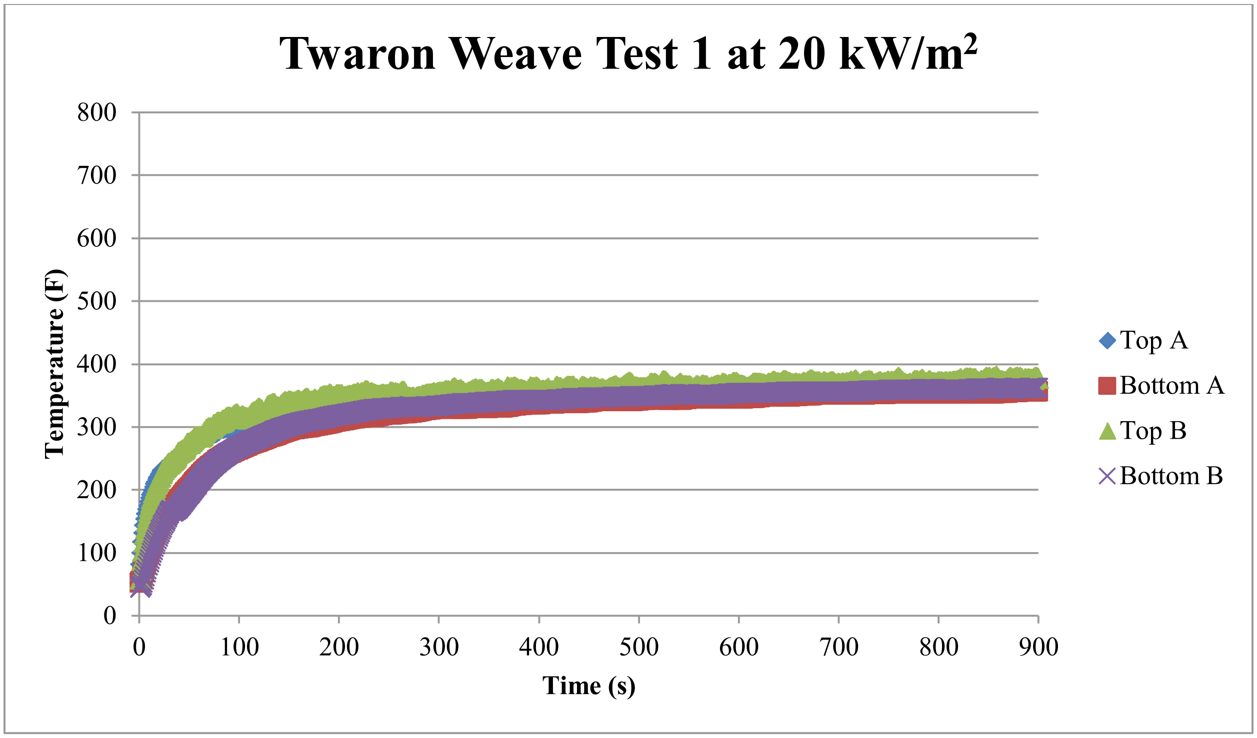

PBI Matrix Test 2 at 20 kW/m2
Temperature (F)
0
100
200
300
400
500
600
700
800
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

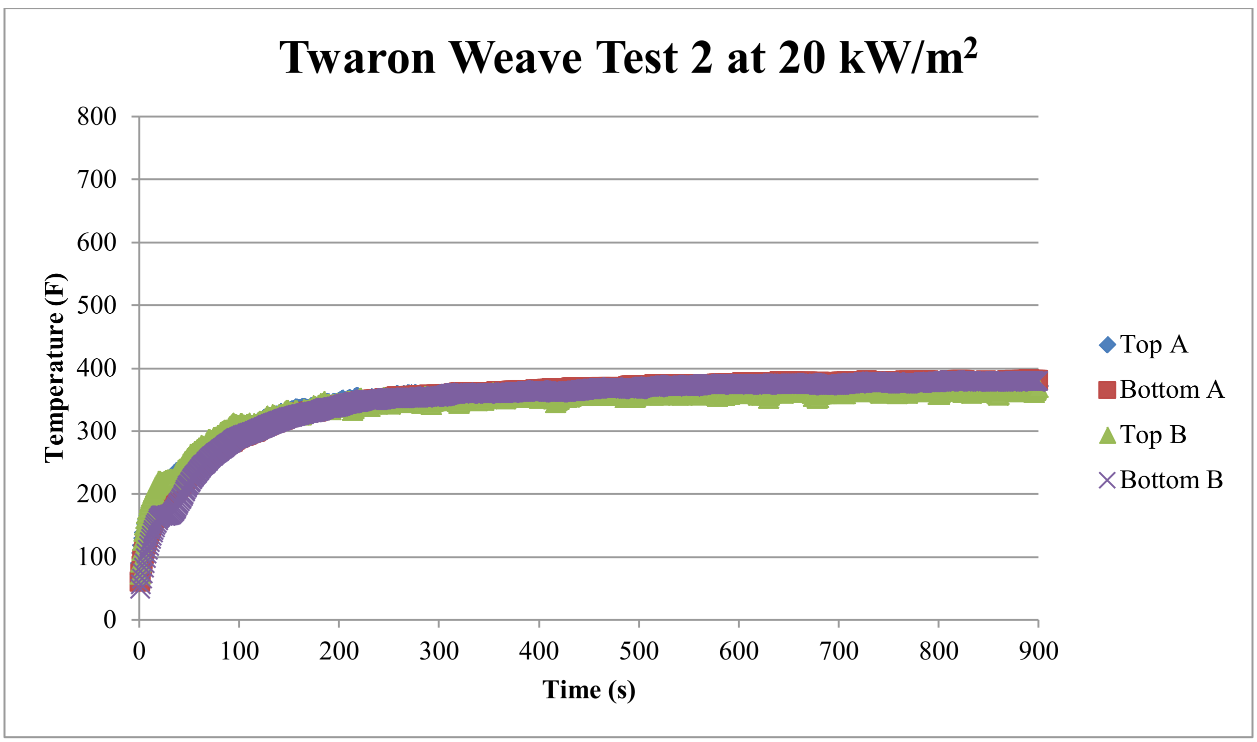


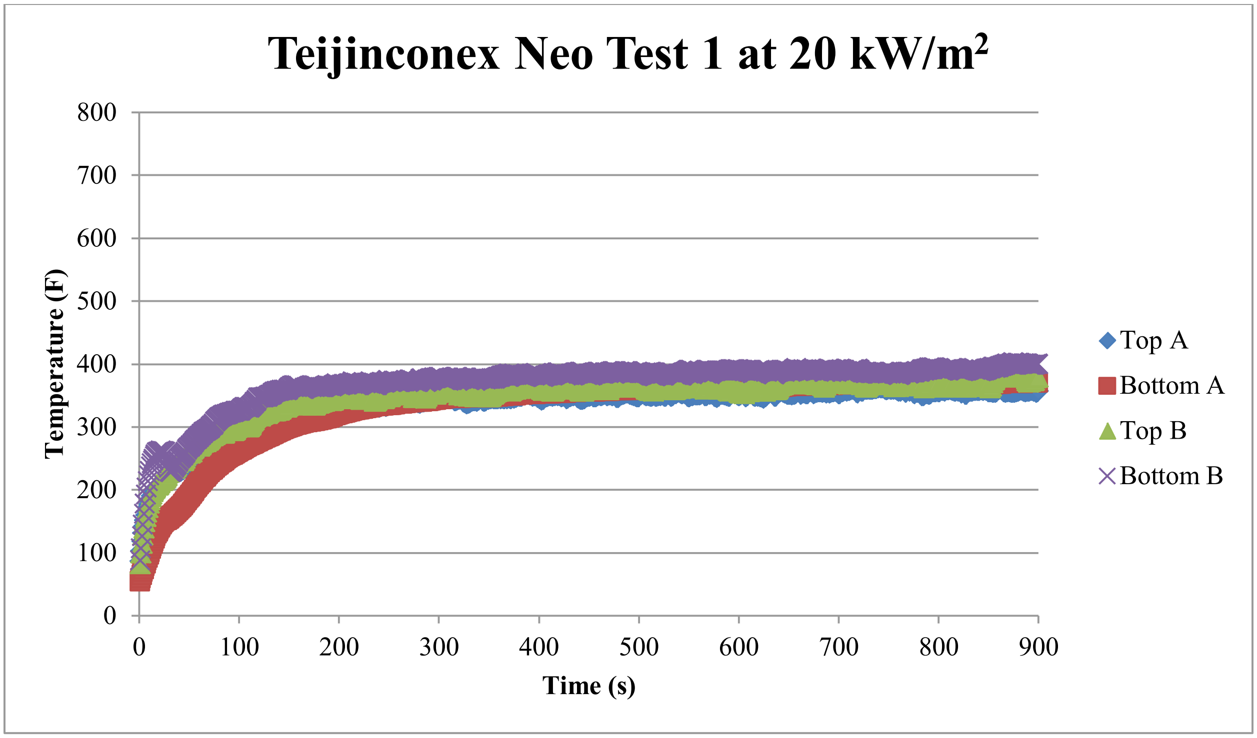
Twaron Knit Test 1 at 20 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

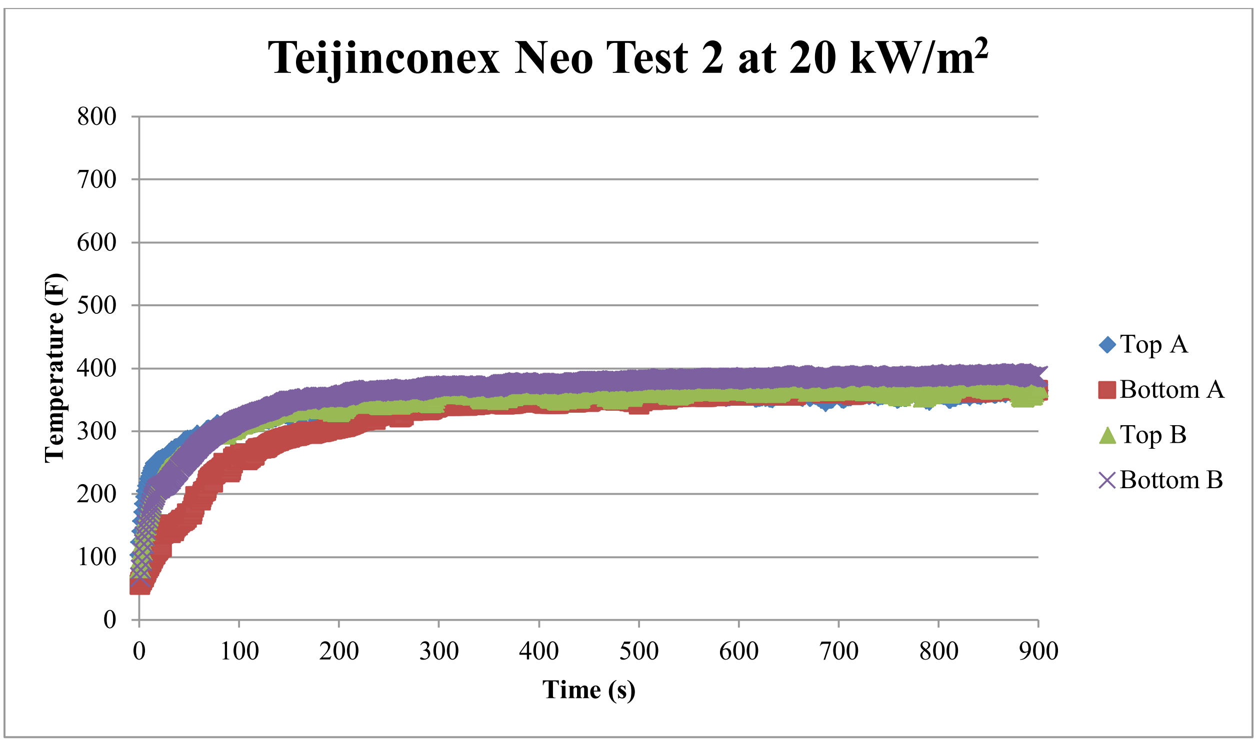


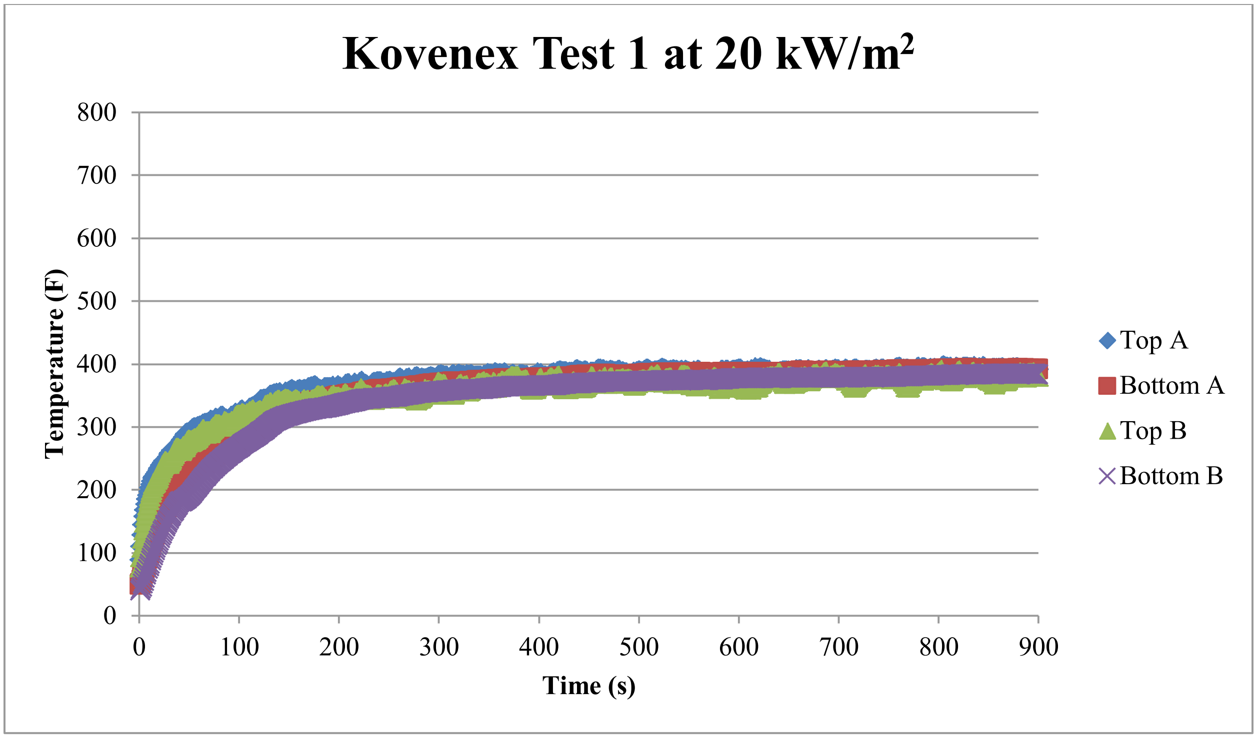
Twaron Knit Test 2 at 20 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

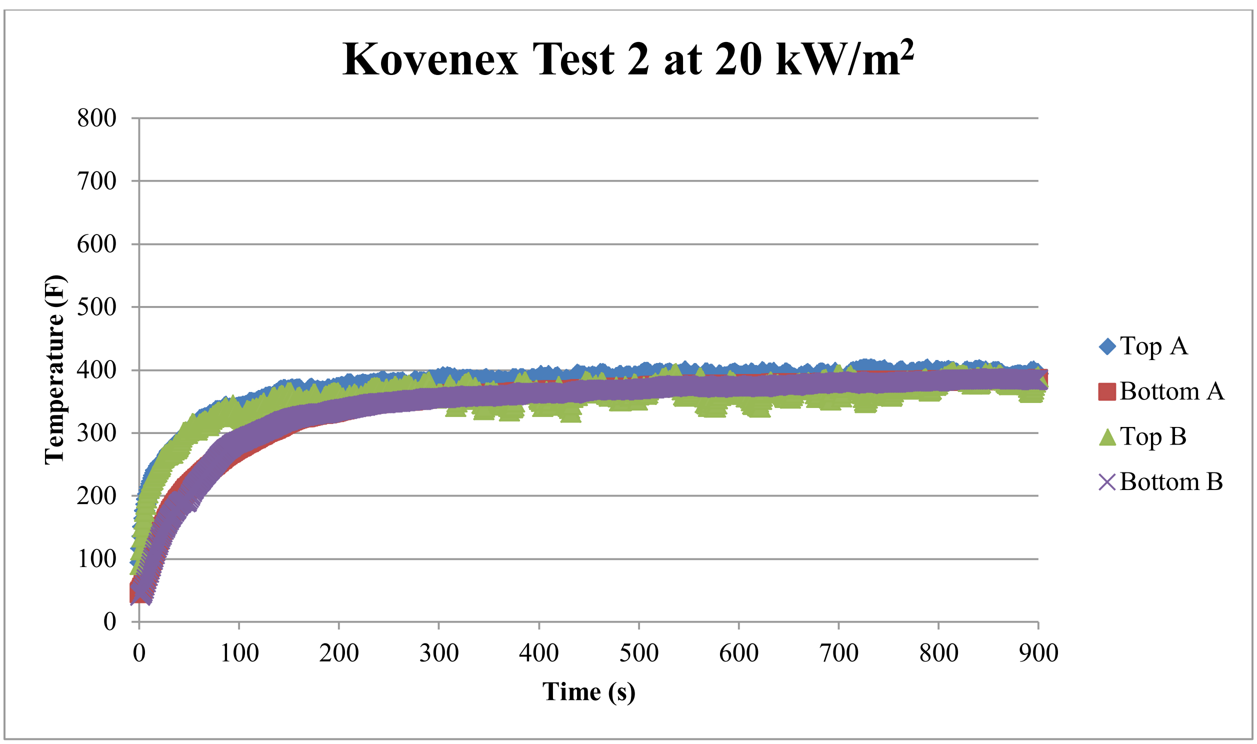

Twaron Weave Test 1 at 20 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

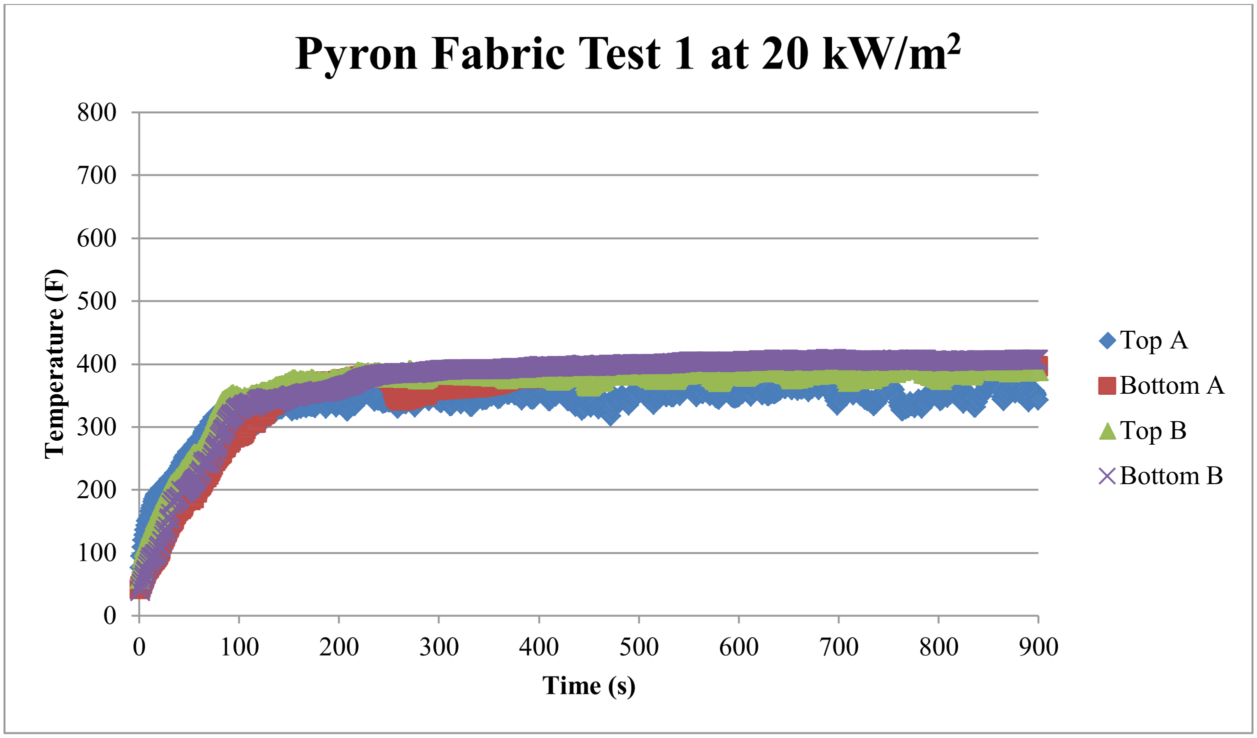

Twaron Weave Test 2 at 20 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

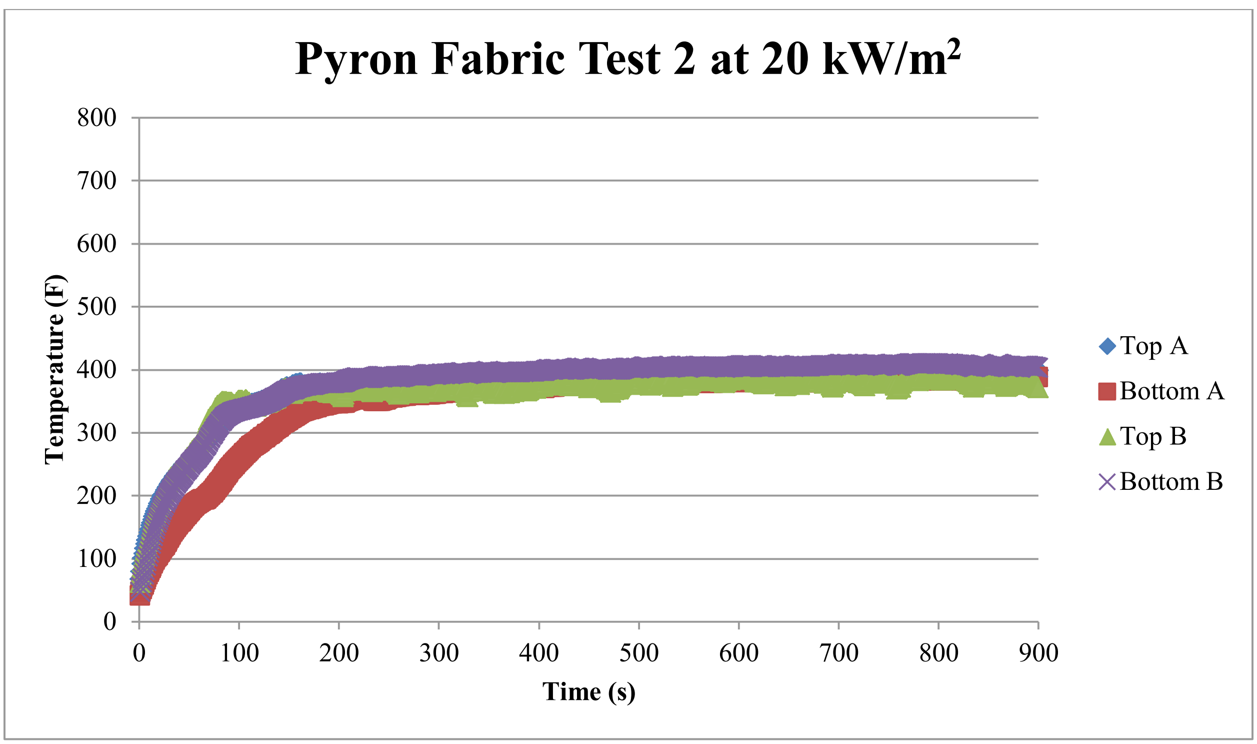

Teijinconex Neo Test 1 at 20 kW/m²
Temperature (F)
Time (s)
Top A
Bottom A
Top B
Bottom B

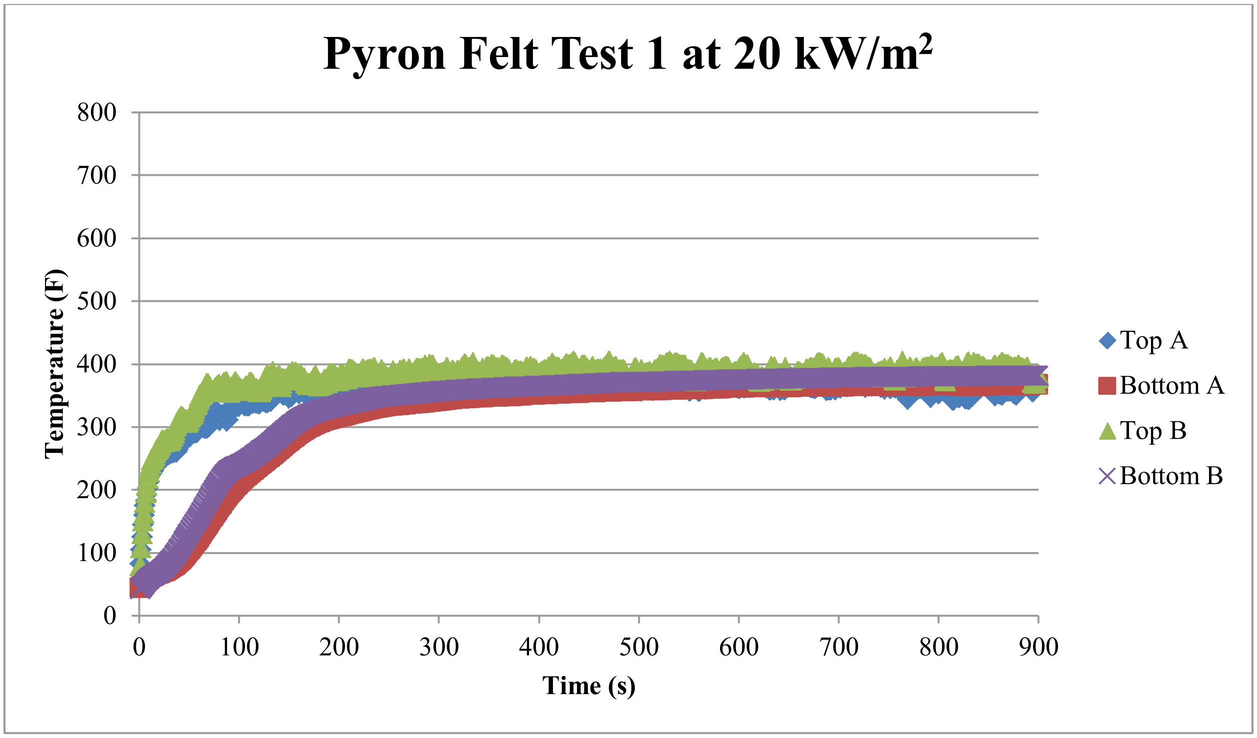

Teijinconex Neo Test 2 at 20 kW/m²
Temperature (F)
Time (s)
Top A
Bottom A
Top B
Bottom B

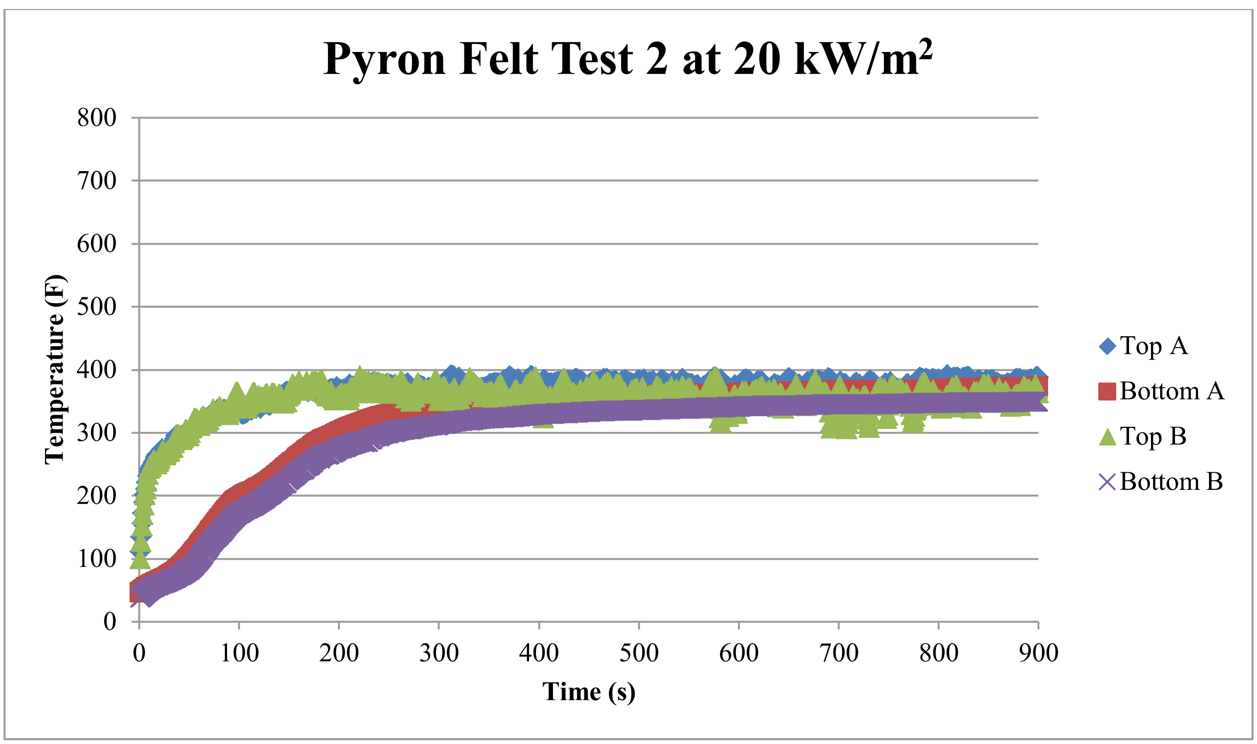

Kovenex Test 1 at 20 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

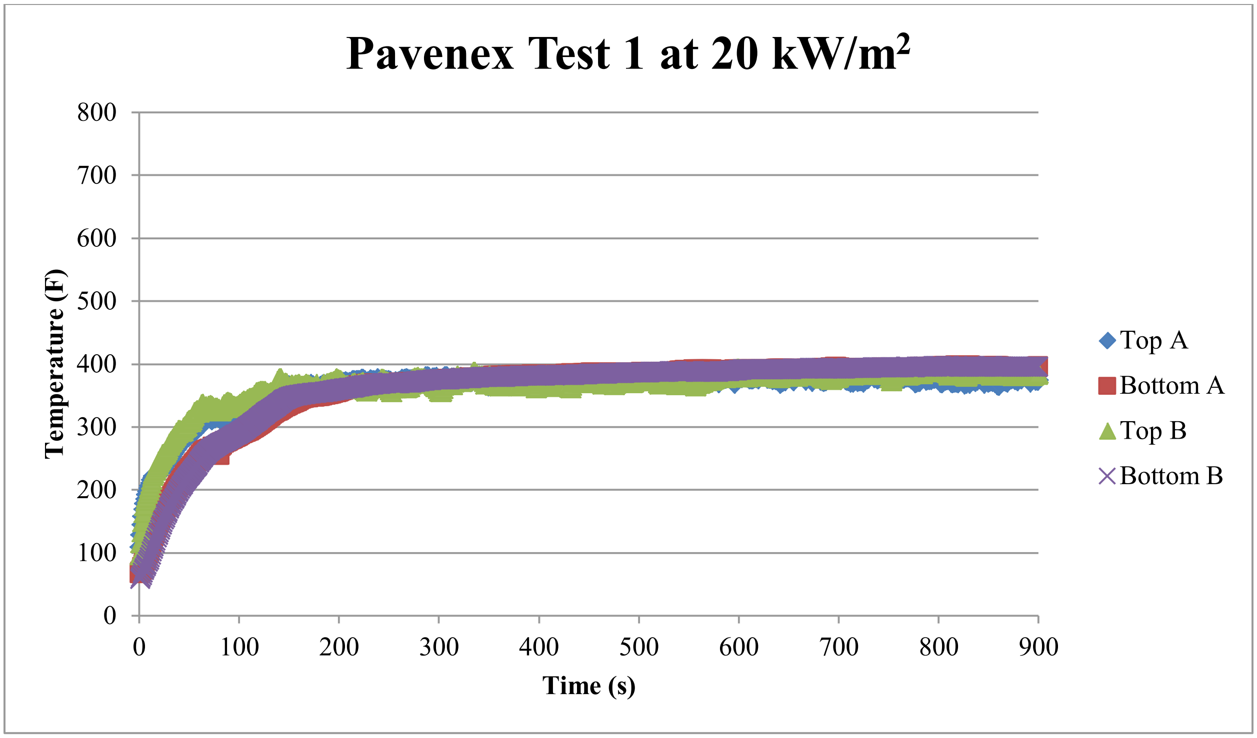

Kovenex Test 2 at 20 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Pyron Fabric Test 1 at 20 kW/m²
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

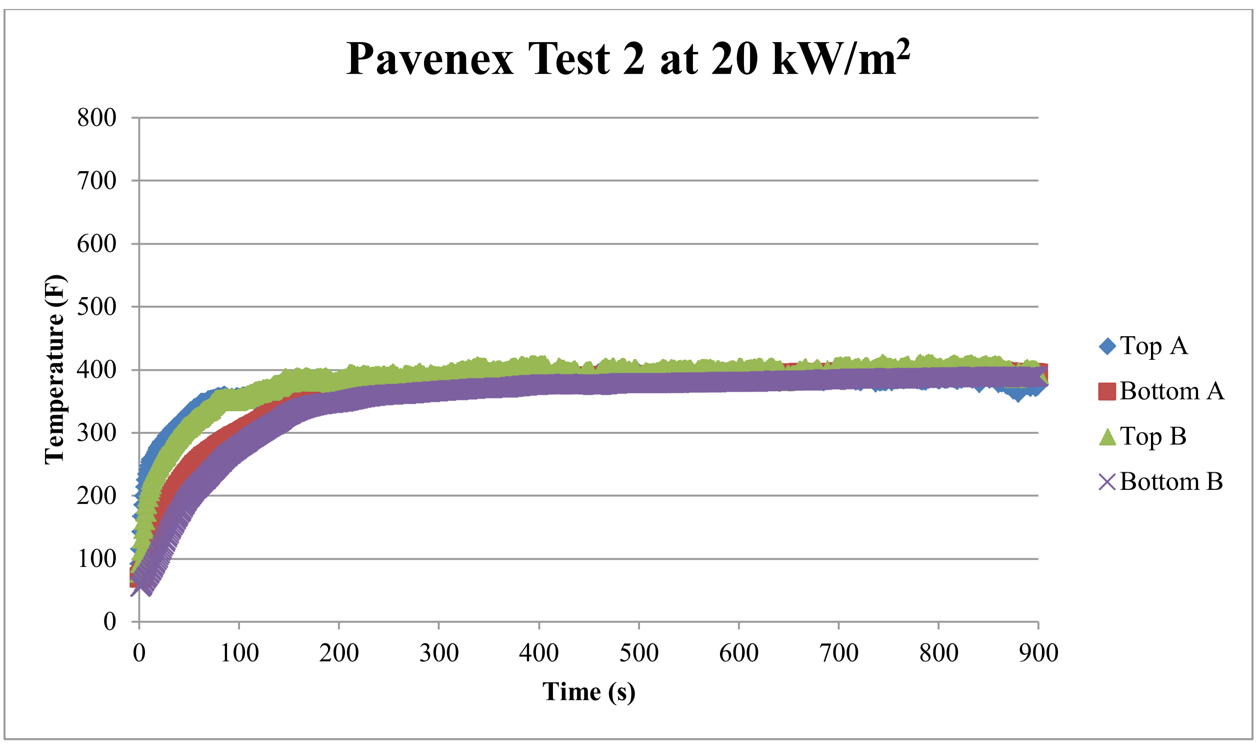

Pyron Fabric Test 2 at 20 kW/m²
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B


Pyron Felt Test 1 at 20 kW/m²
800
700
600
500
400
300
200
100
0
Temperature (F)
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

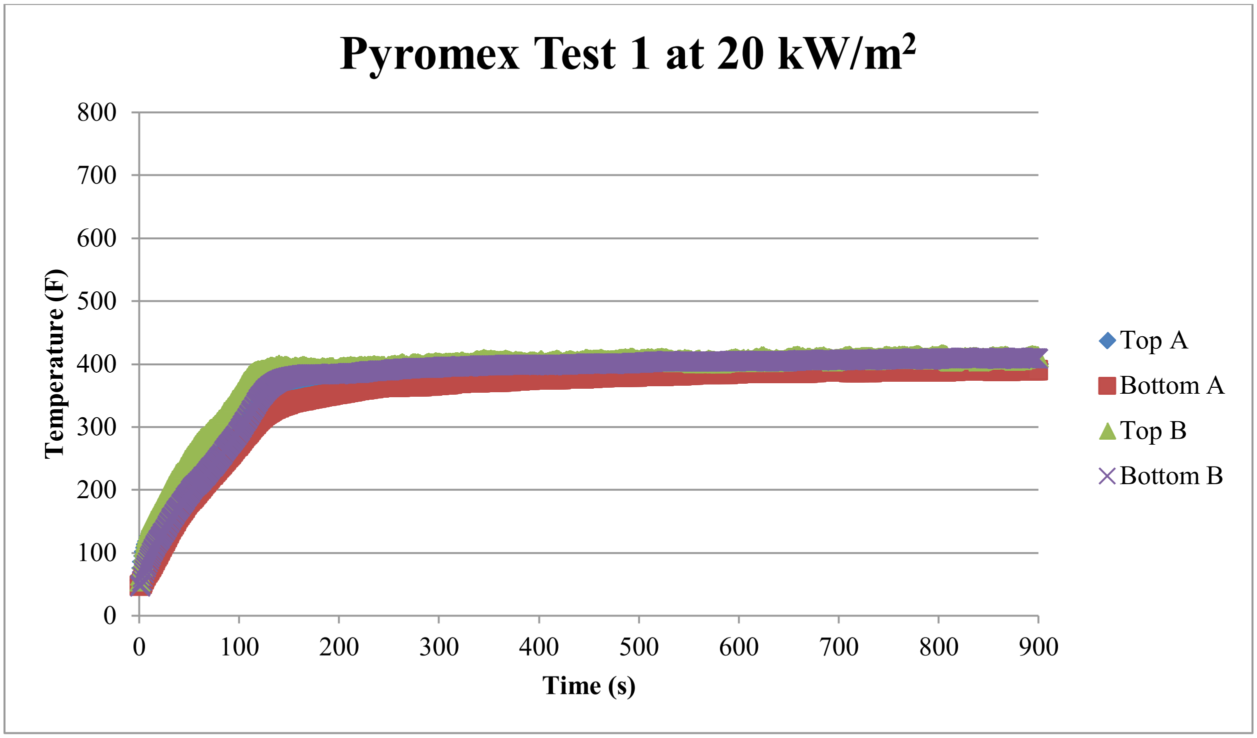

Pyron Felt Test 2 at 20 kW/m²
800
700
600
500
400
300
200
100
0
Temperature (F)
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

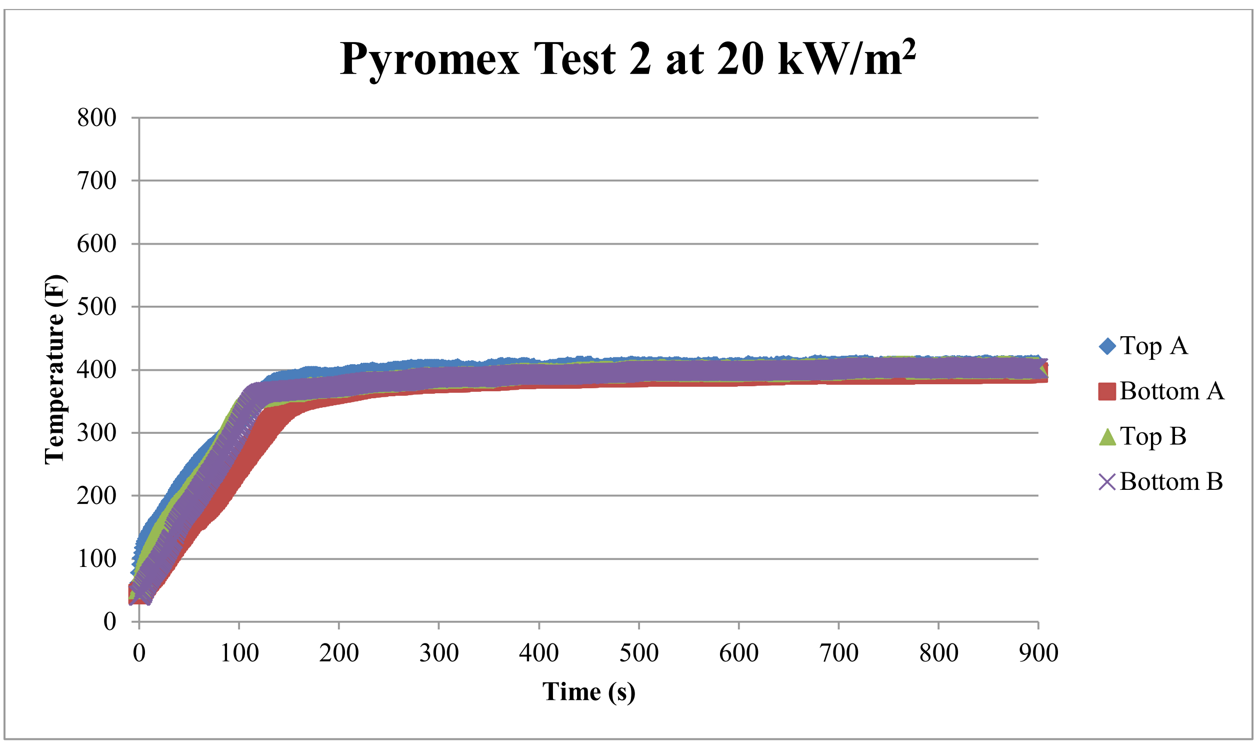


Pavenex Test 1 at 20 kW/m²
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

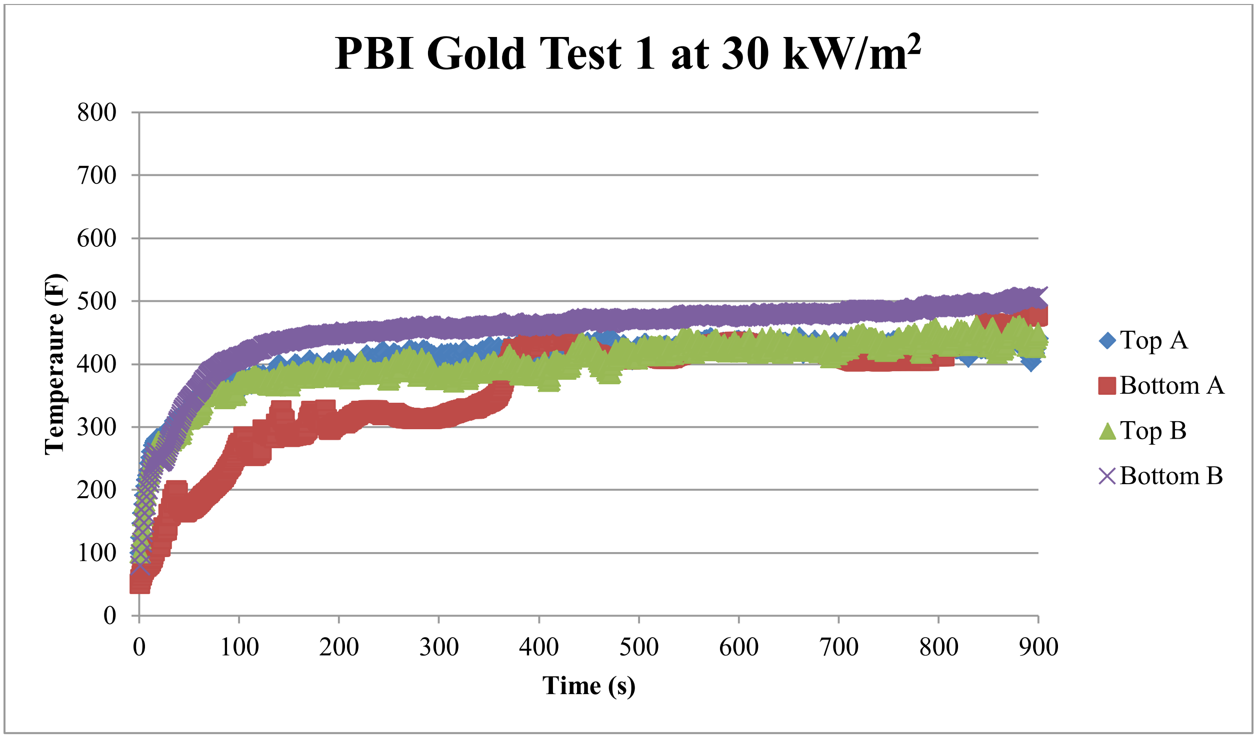


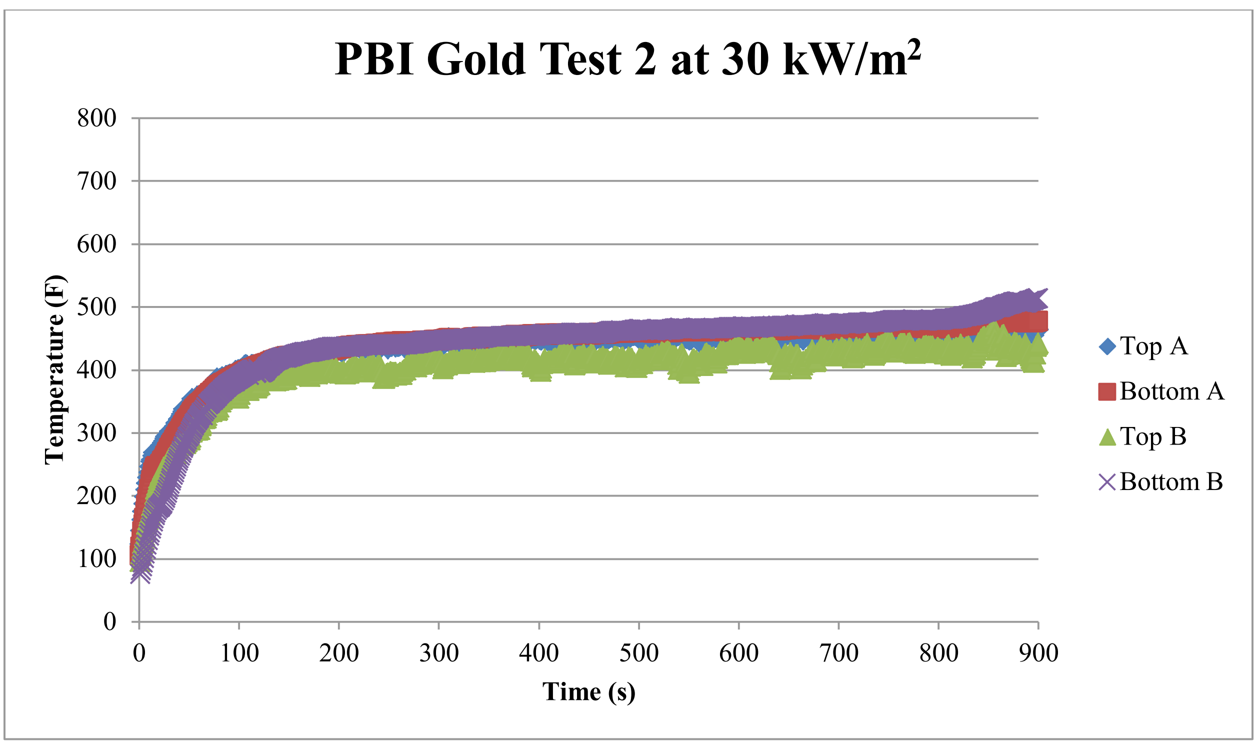
Pavenex Test 2 at 20 kW/m²
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

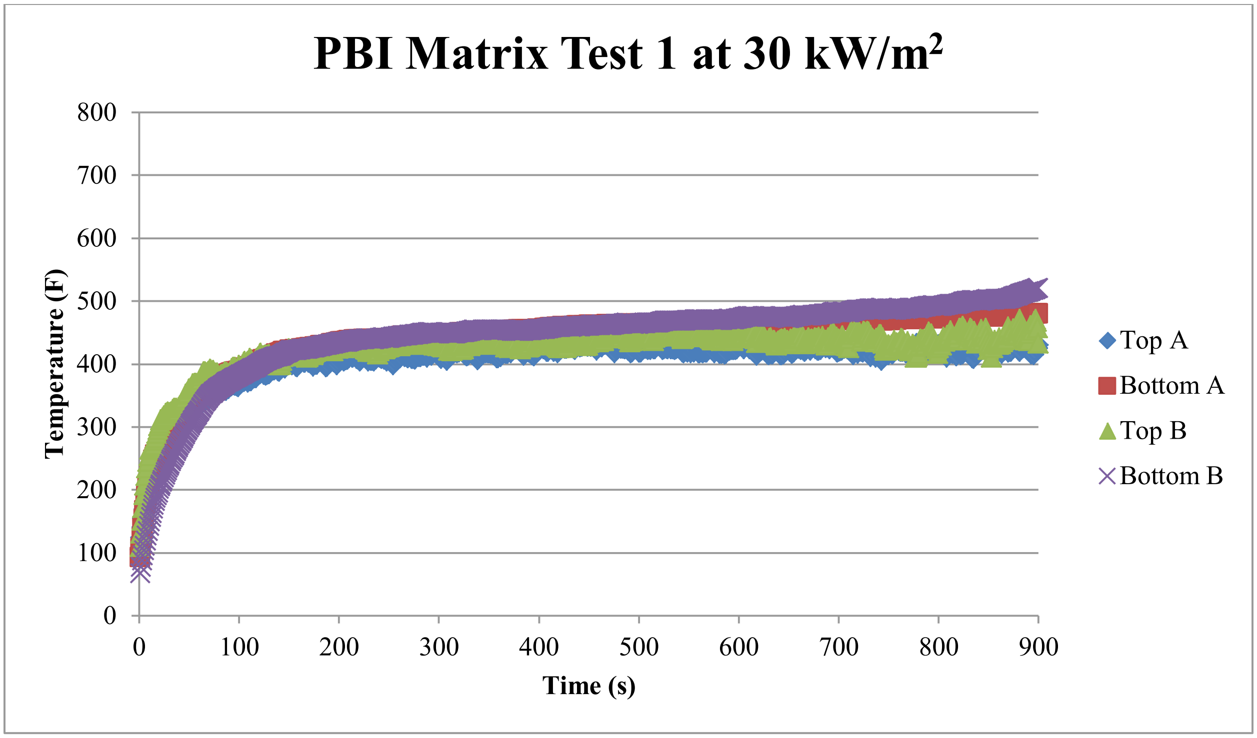


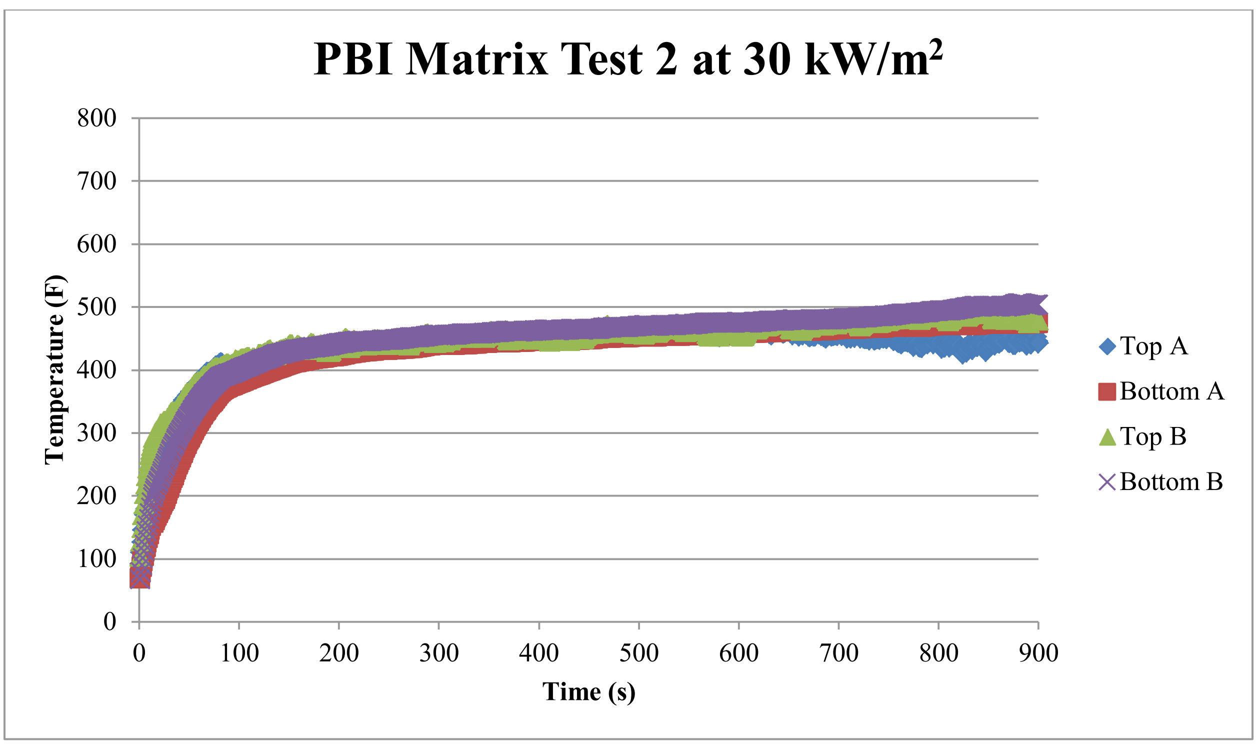


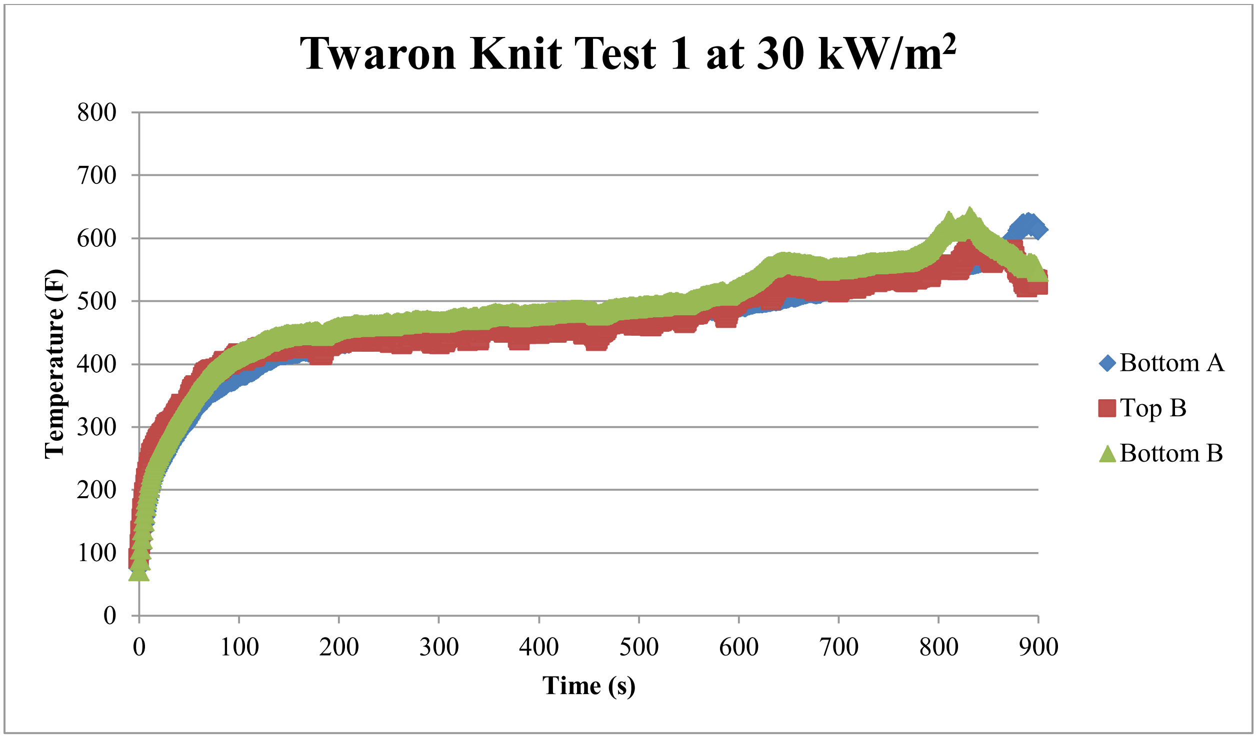
Heat Flux of 30 kW/m^2

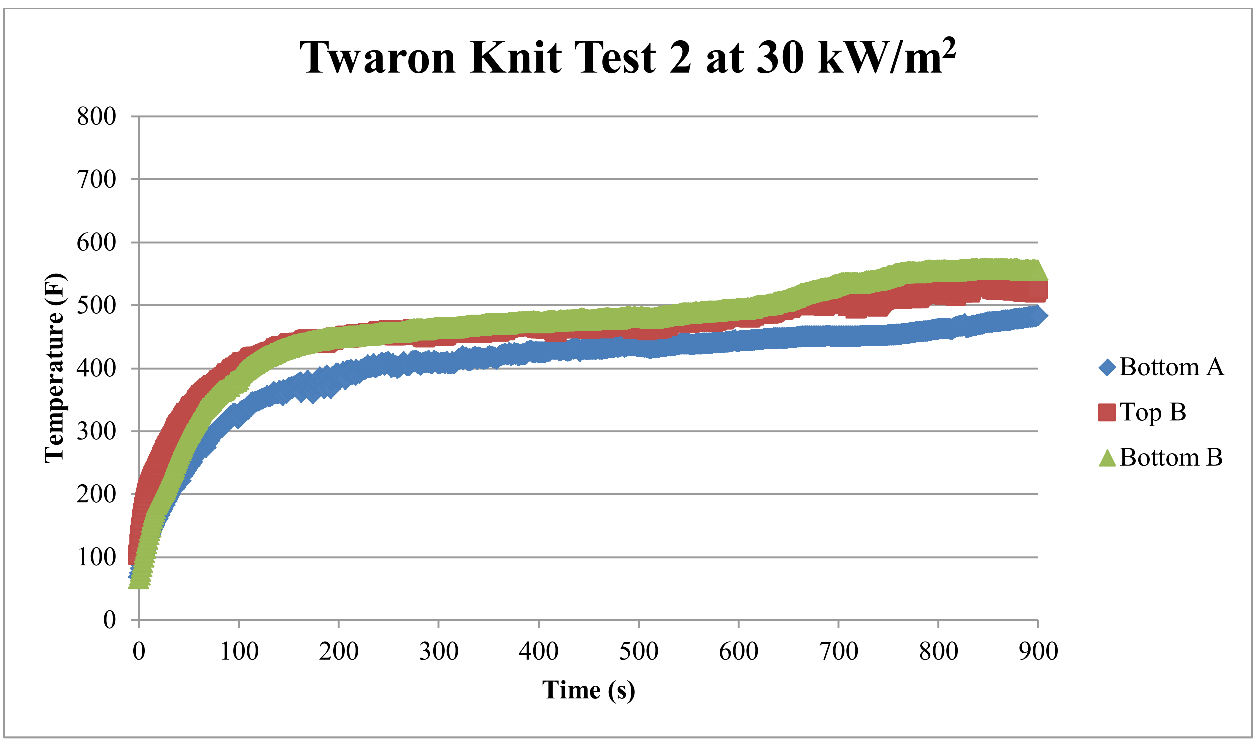

PBI Gold Test 1 at 30 kW/m2
Temperaure (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

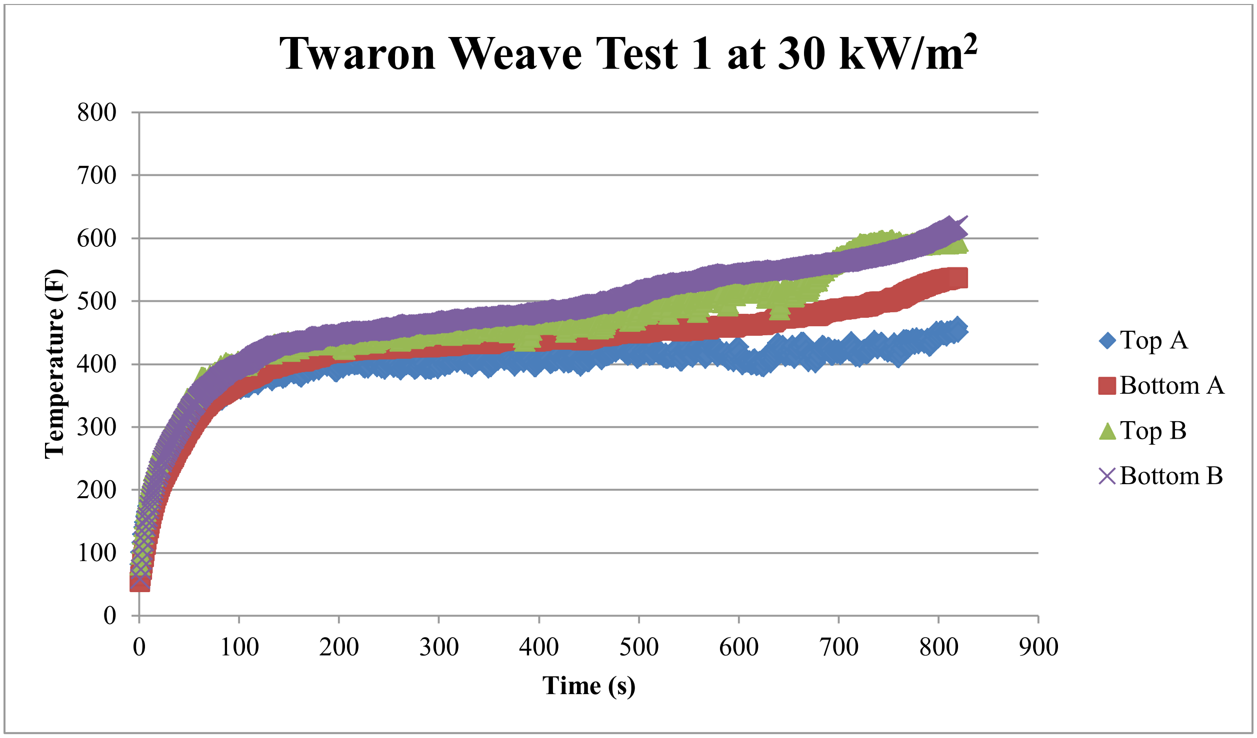

PBI Gold Test 2 at 30 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


PBI Matrix Test 1 at 30 kW/m2
Temperature (F)
Time (s)
Top A
Bottom A
Top B
Bottom B

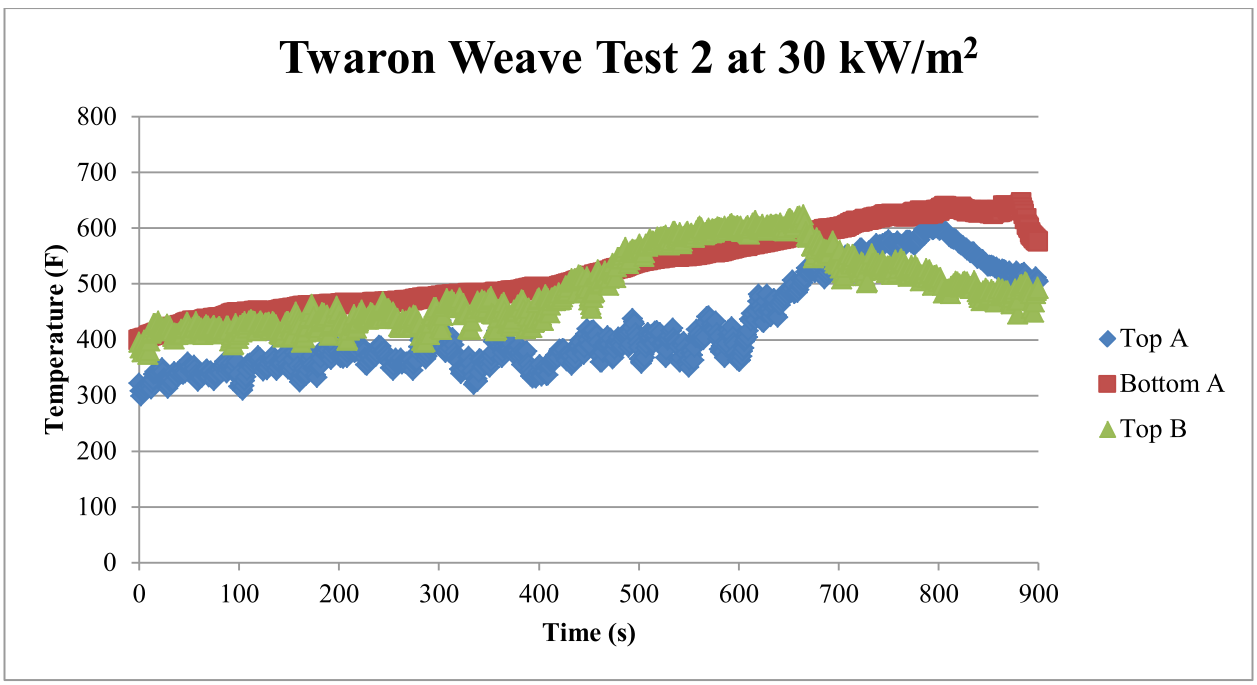

PBI Matrix Test 2 at 30 kW/m2
Temperature (F)
Time (s)
Top A
Bottom A
Top B
Bottom B


Twaron Knit Test 1 at 30 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Bottom A
Top B
Bottom B

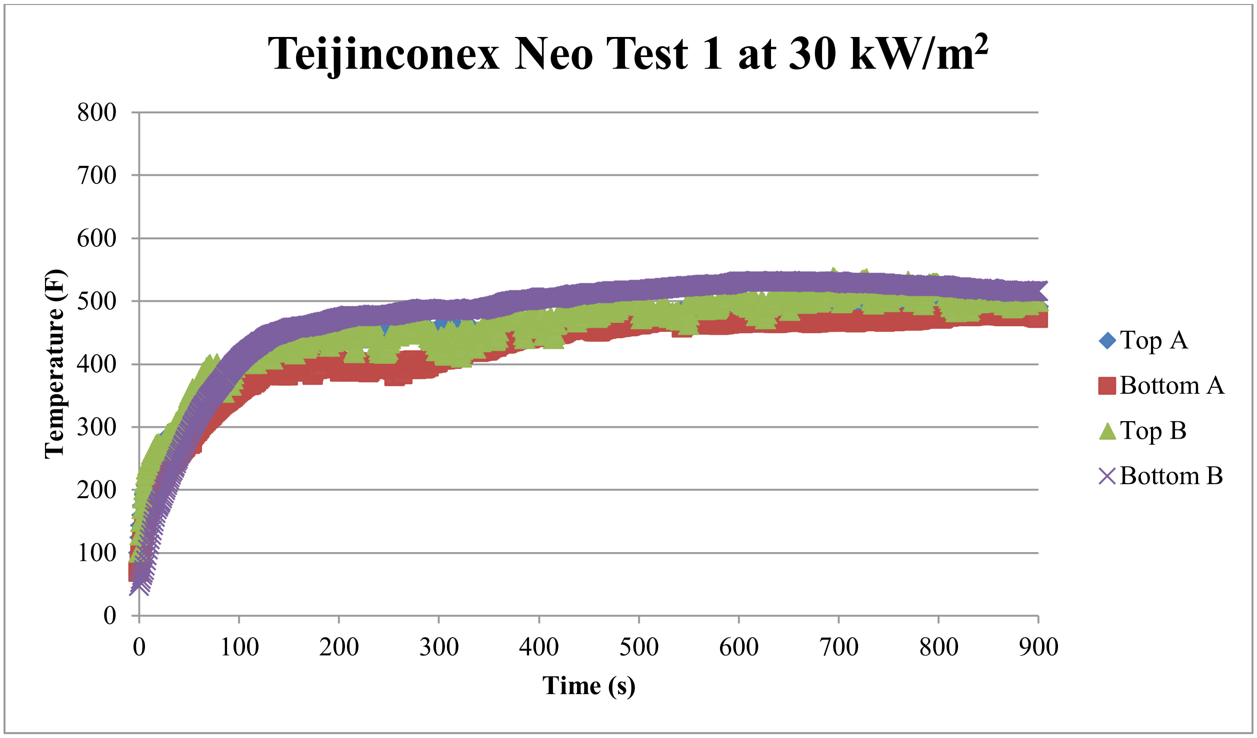

Twaron Knit Test 2 at 30 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Bottom A
Top B
Bottom B



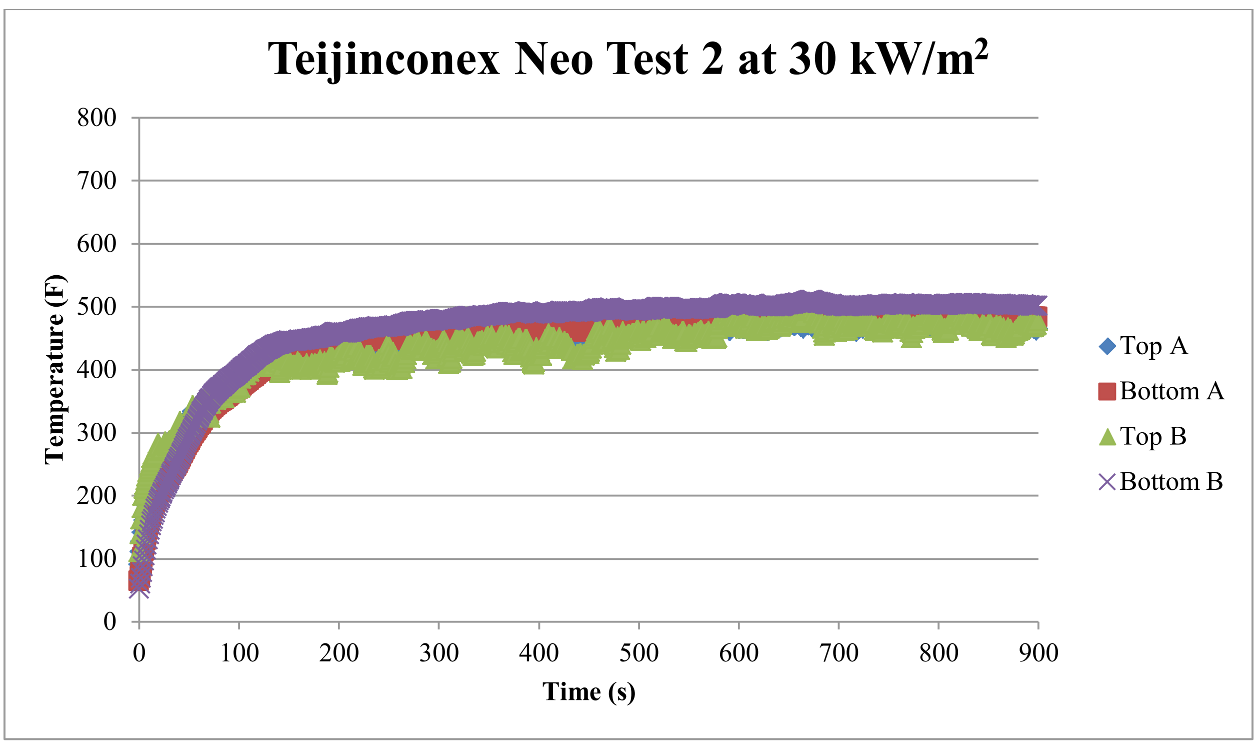
Twaron Weave Test 1 at 30 kW/m²
Temperature (F)
Time (s)
Top A
Bottom A
Top B
Bottom B



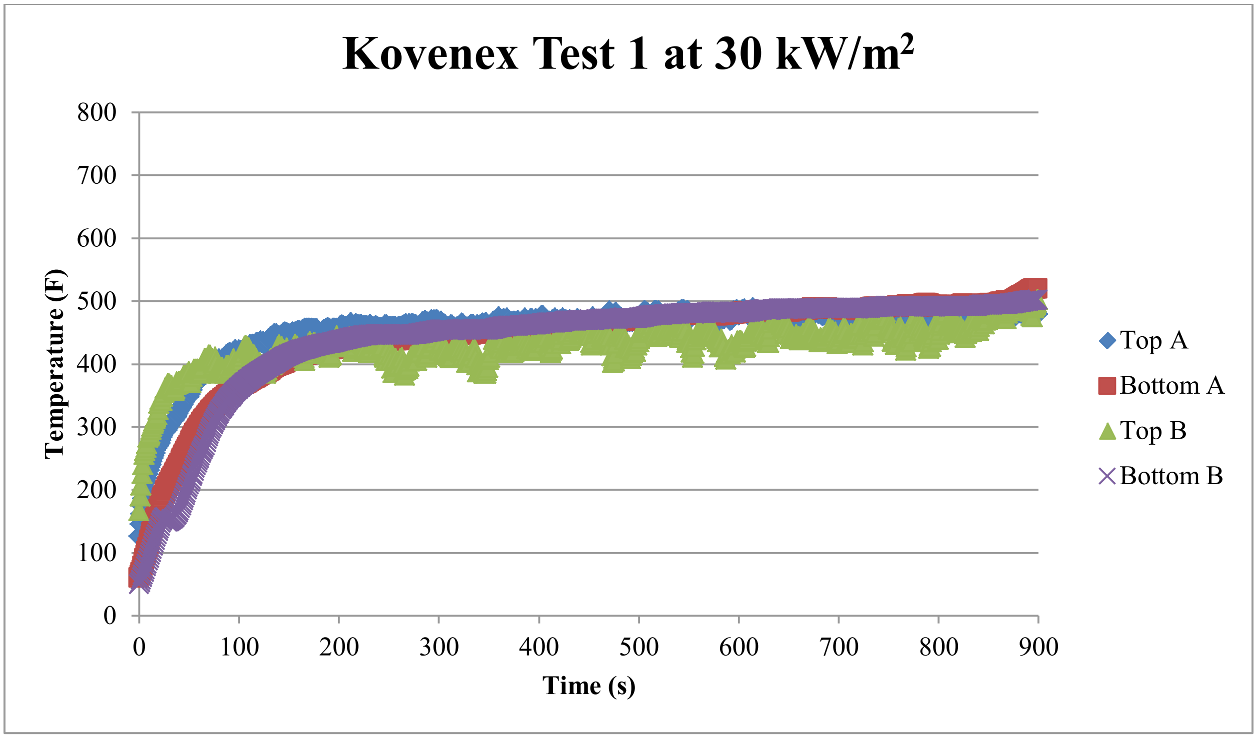
Twaron Weave Test 2 at 30 kW/m²
Temperature (F)
Time (s)
Top A
Bottom A
Top B

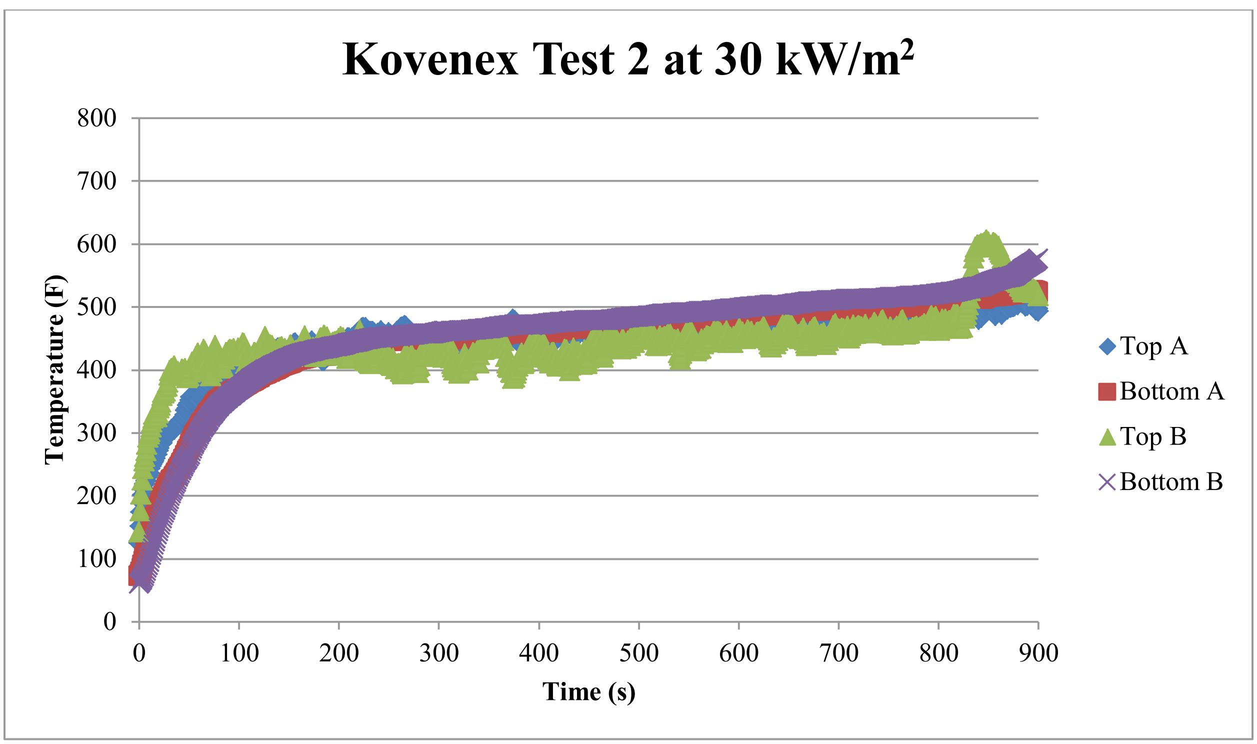


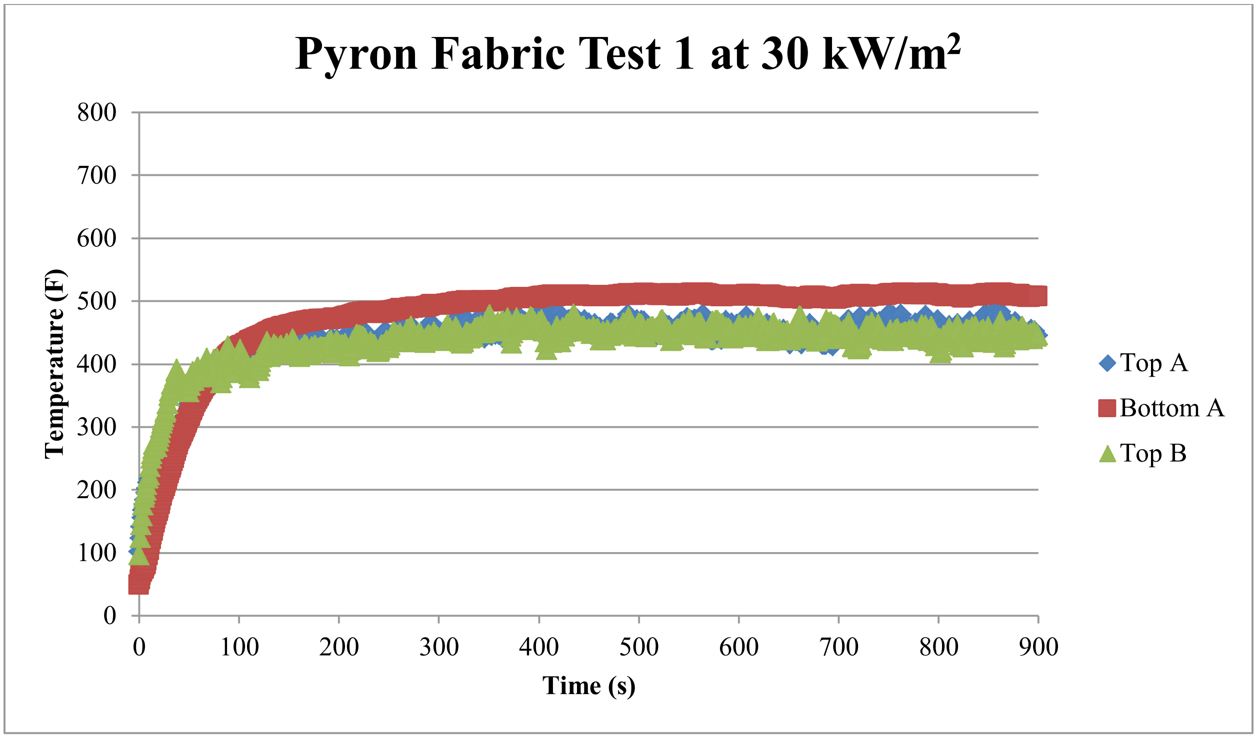
Teijinconex Neo Test 1 at 30 kW/m²
Temperature (F)
0
100
200
300
400
500
600
700
800
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

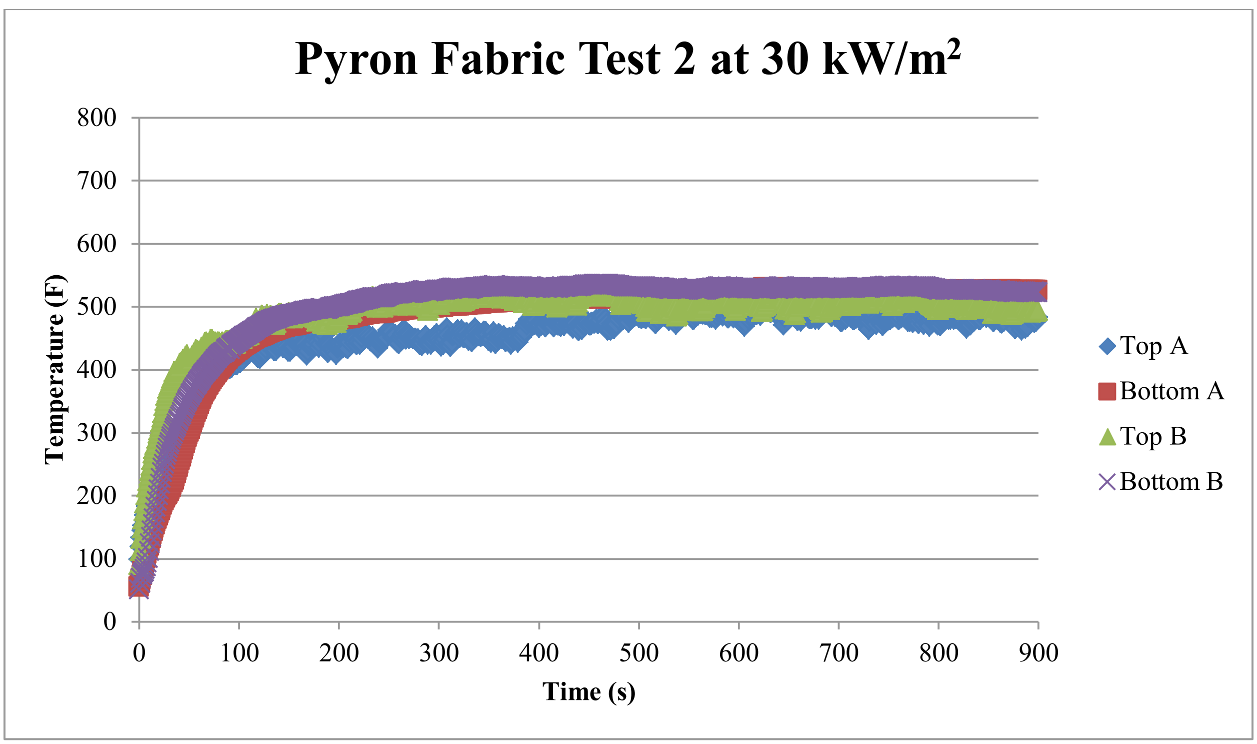


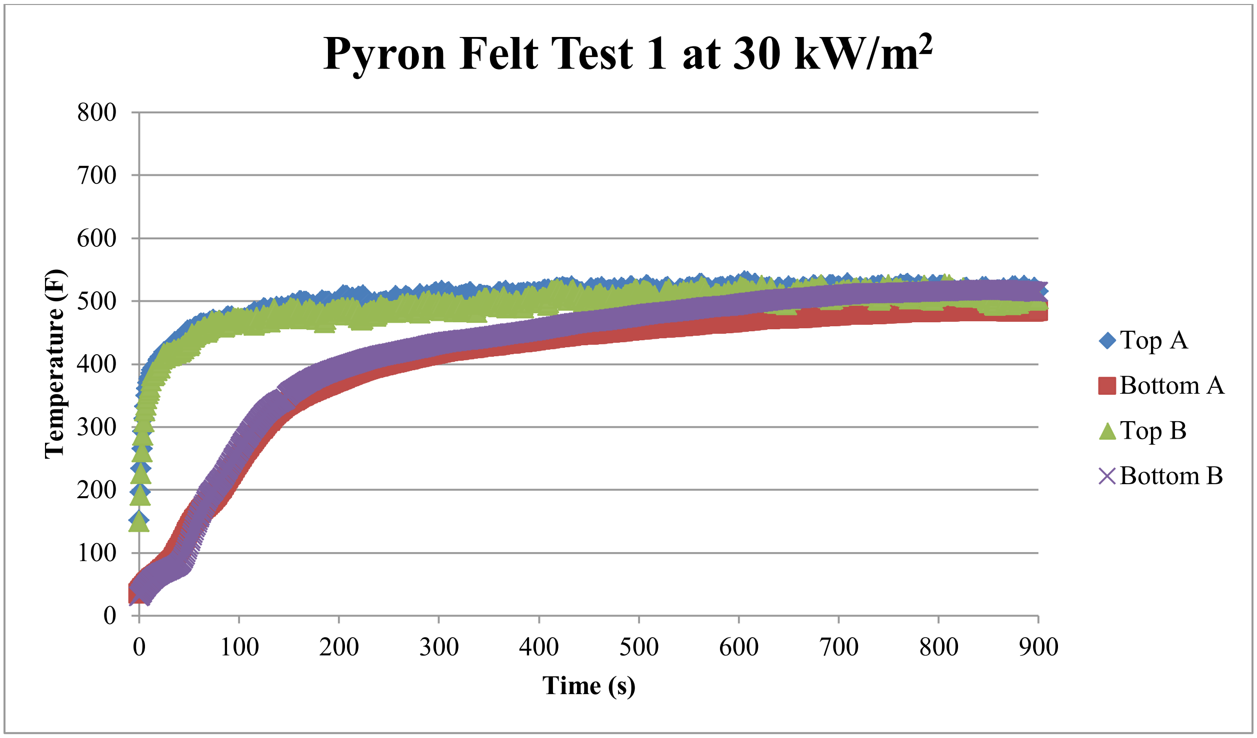
Teijinconex Neo Test 2 at 30 kW/m²
Temperature (F)
0
100
200
300
400
500
600
700
800
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

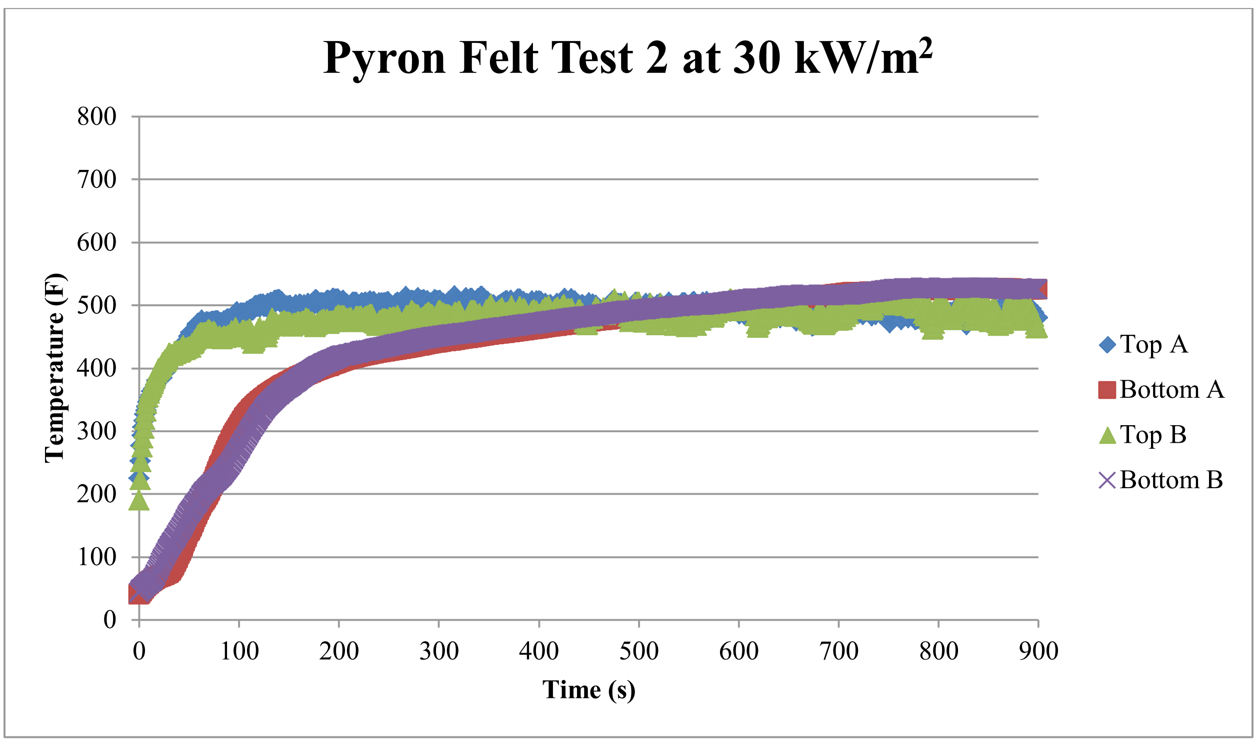

Kovenex Test 1 at 30 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

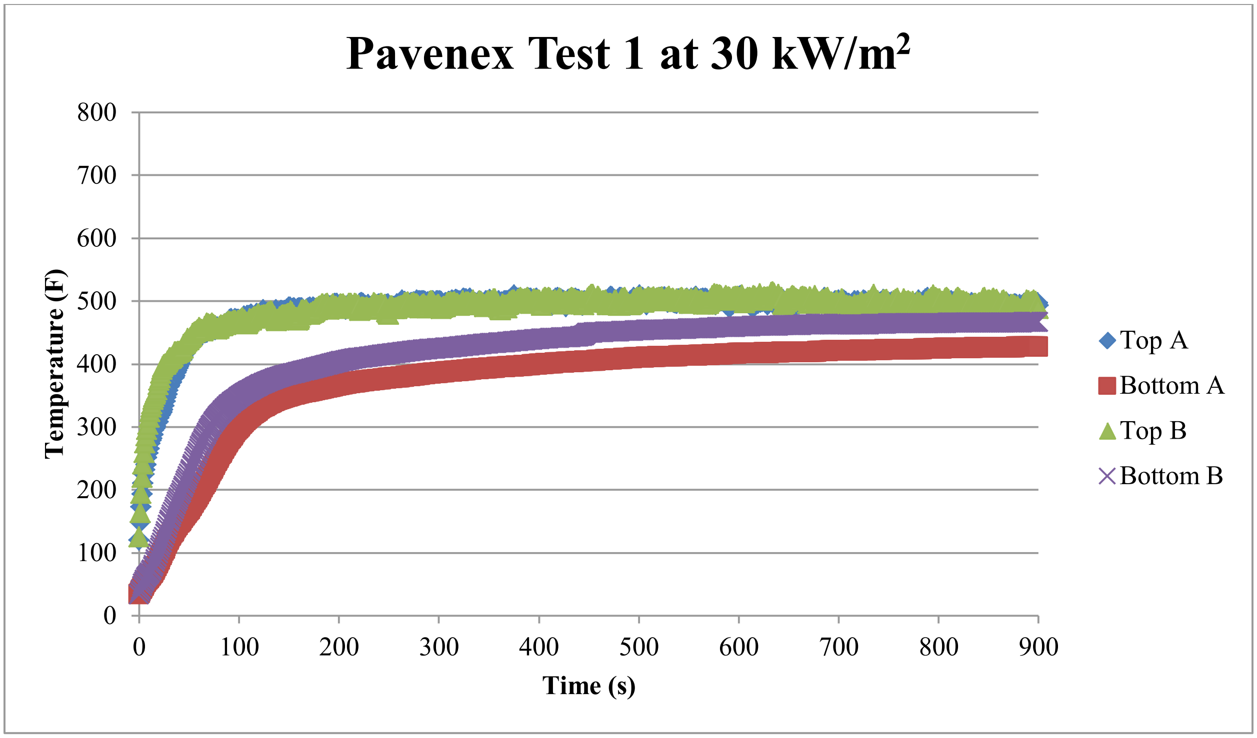

Kovenex Test 2 at 30 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Pyron Fabric Test 1 at 30 kW/m2
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B

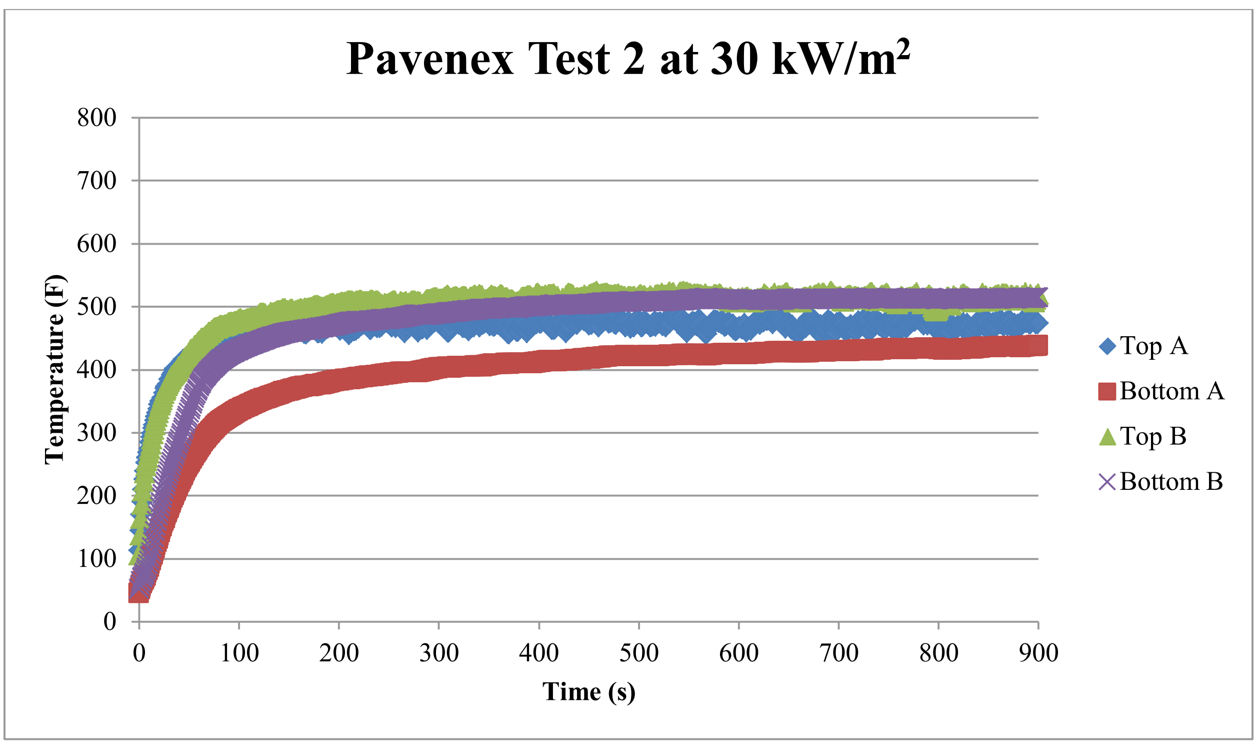

Pyron Fabric Test 2 at 30 kW/m2
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B


Pyron Felt Test 1 at 30 kW/m2
Temperature (F)
0
100
200
300
400
500
600
700
800
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

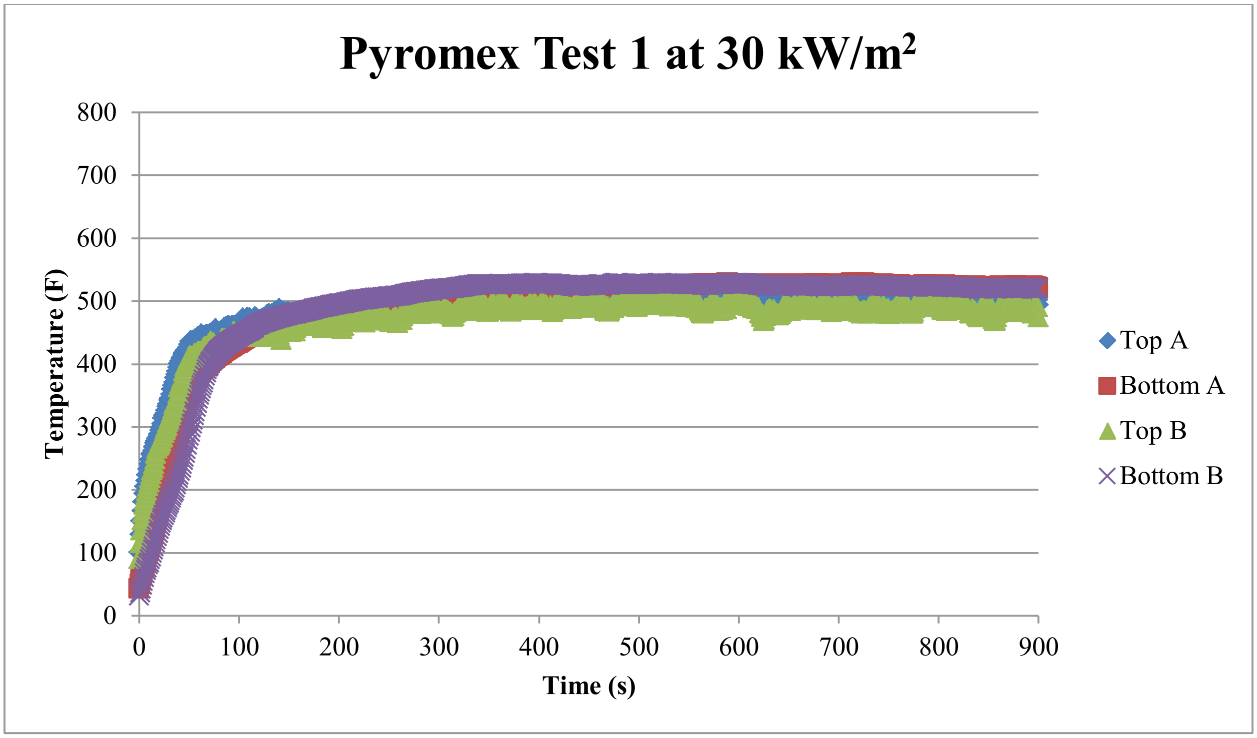

Pyron Felt Test 2 at 30 kW/m2
Temperature (F)
0
100
200
300
400
500
600
700
800
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

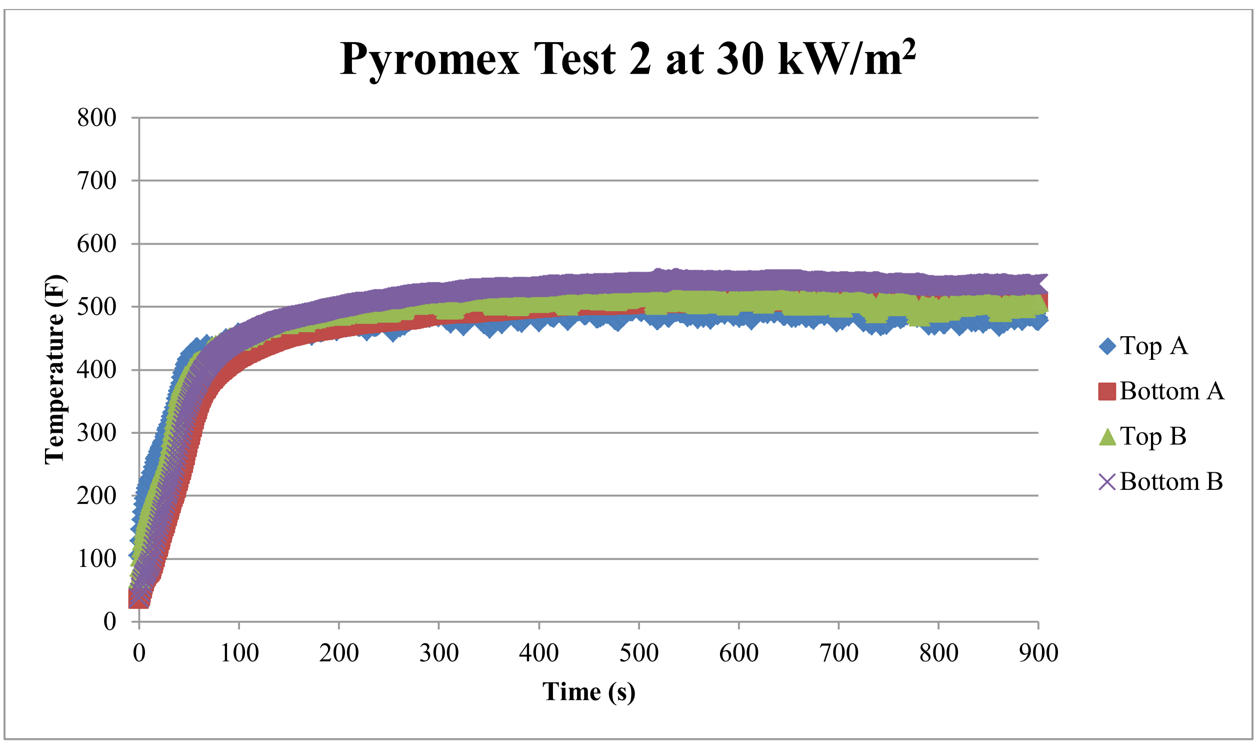


Pavenex Test 1 at 30 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

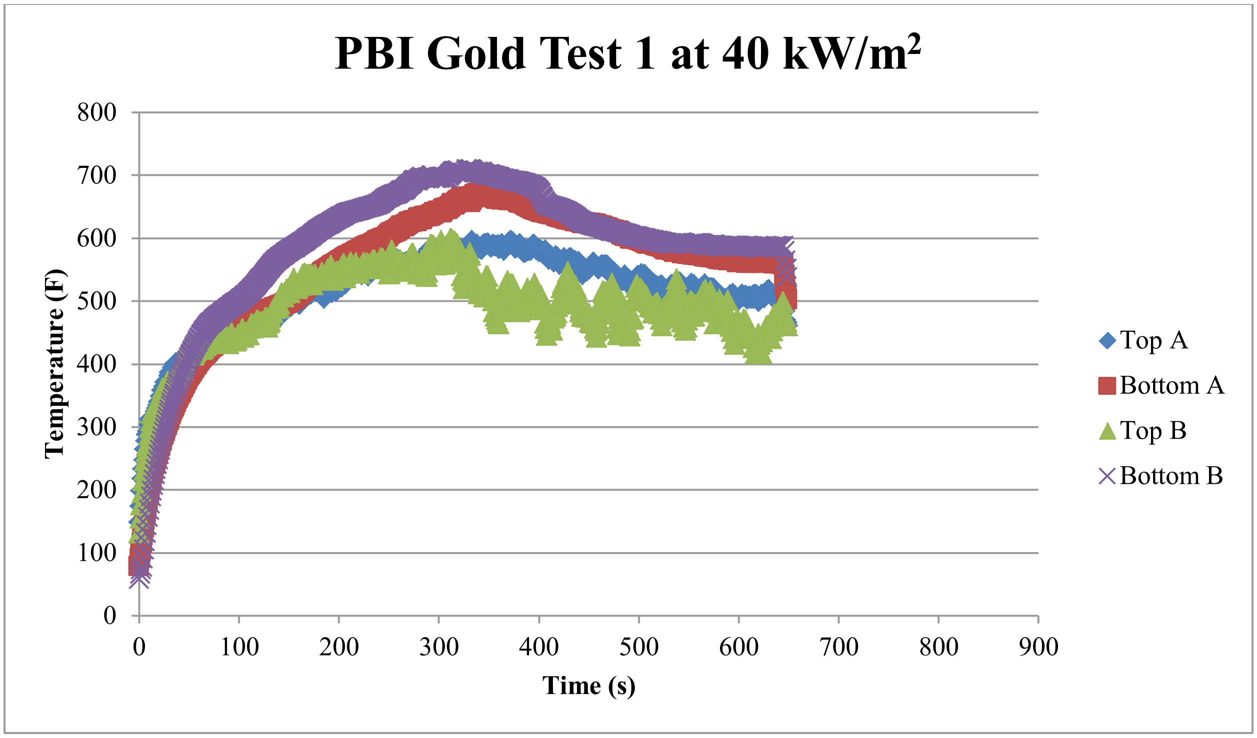


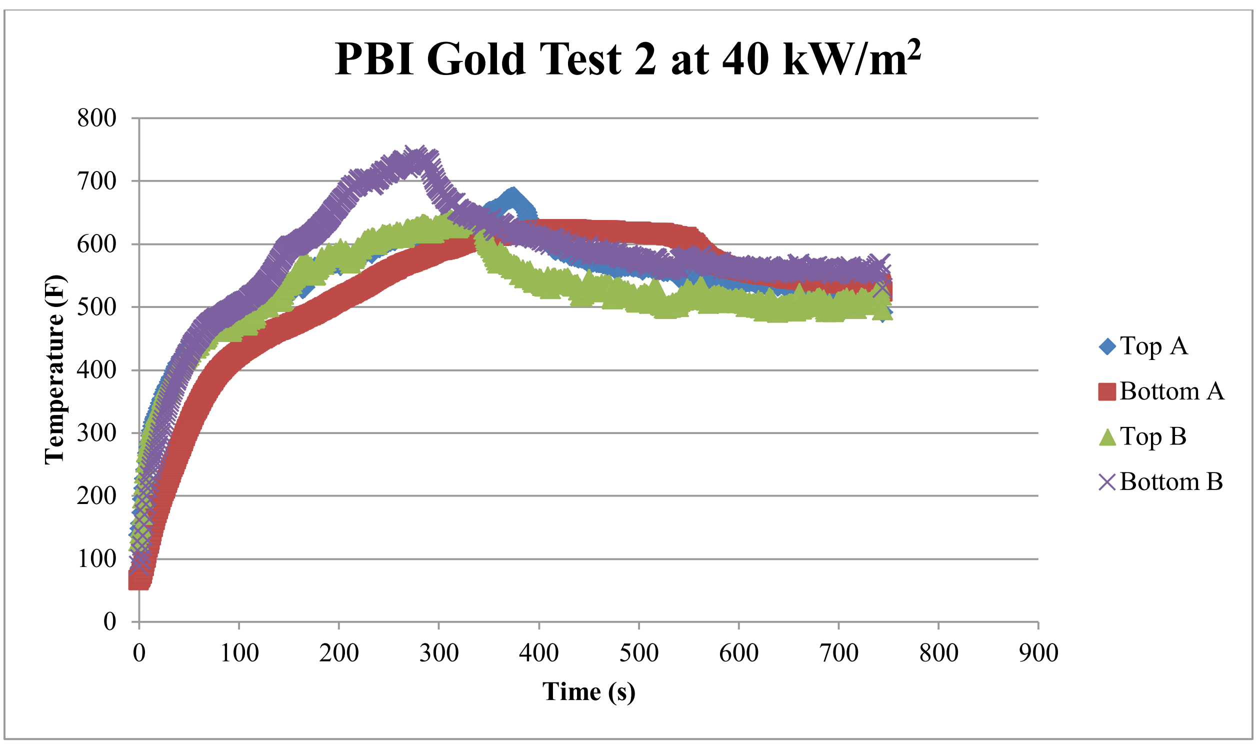
Pavenex Test 2 at 30 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

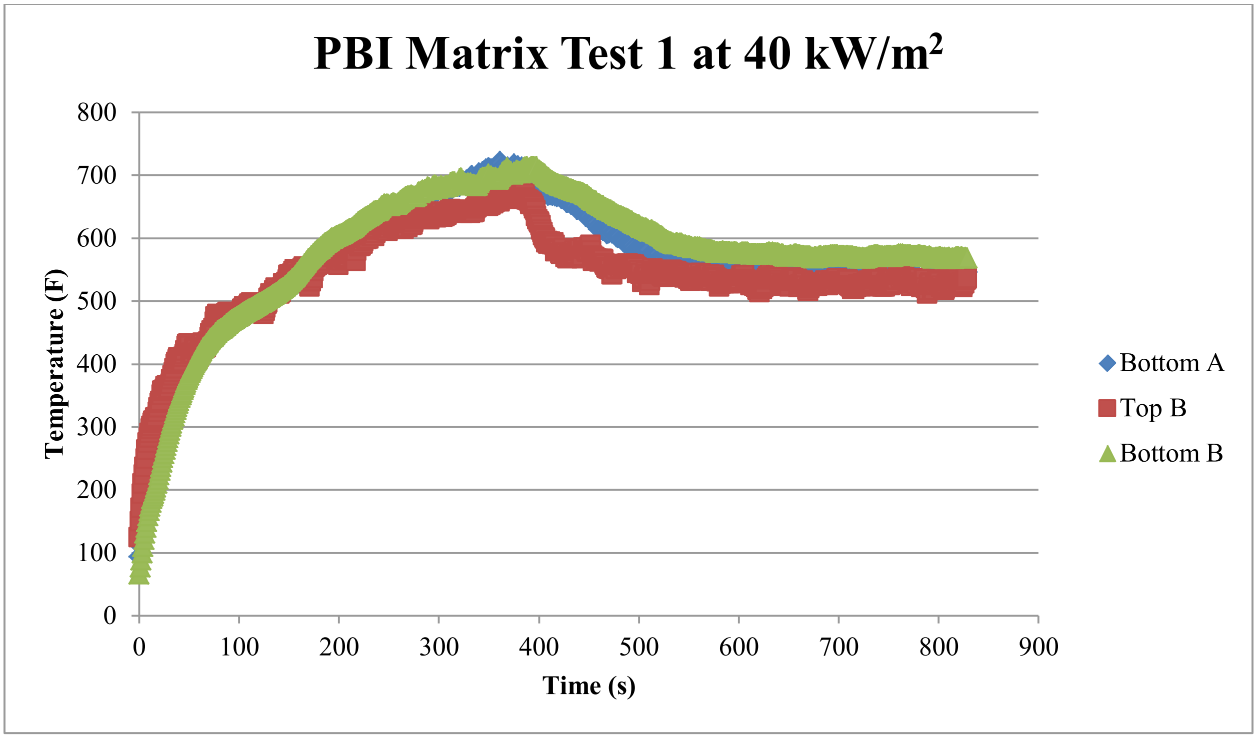

Pyromex Test 1 at 30 kW/m2
800
700
600
500
400
300
200
100
0
Temperature (F)
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

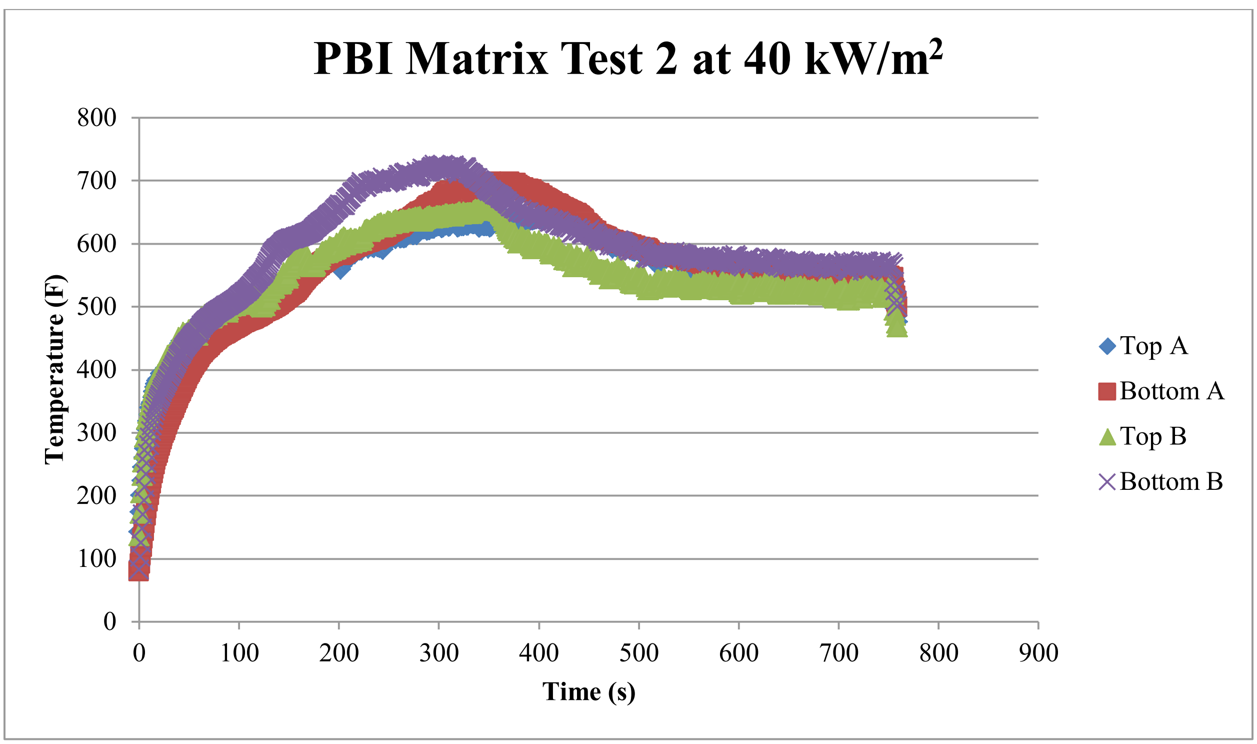

Pyromex Test 2 at 30 kW/m2
800
700
600
500
400
300
200
100
0
Temperature (F)
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

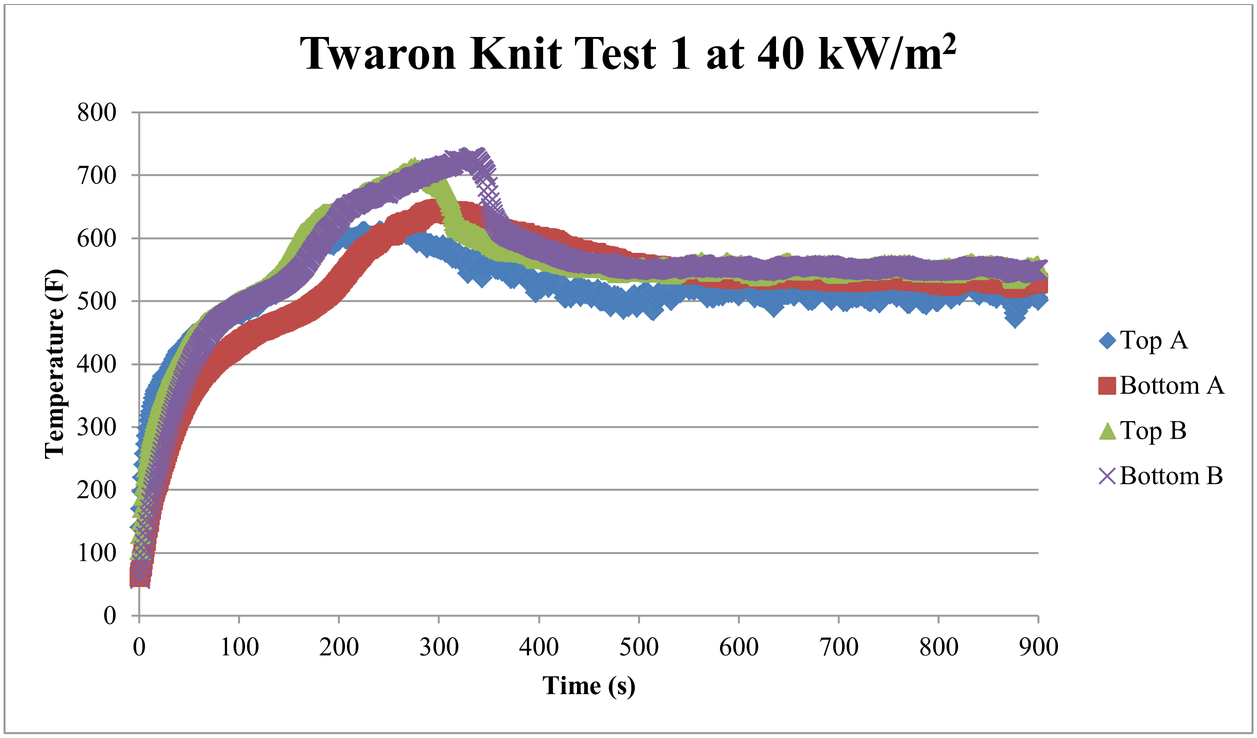
Heat Flux of 40 kW/m^2

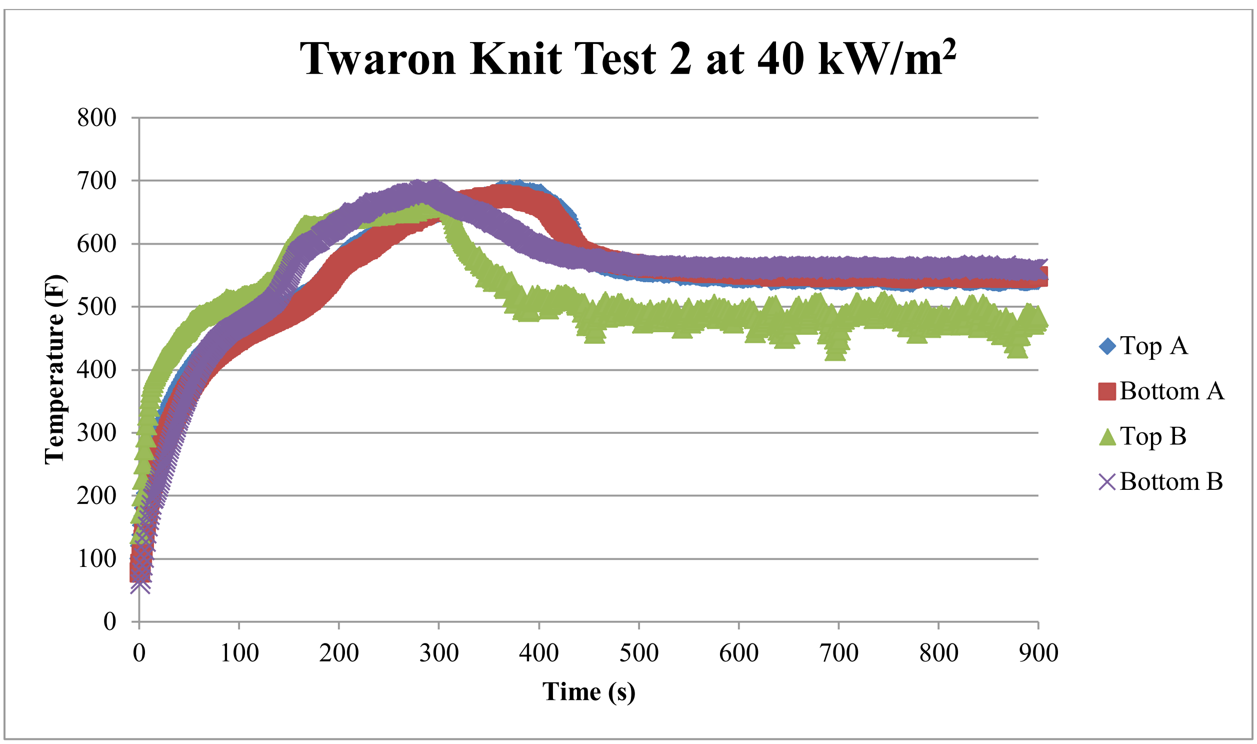


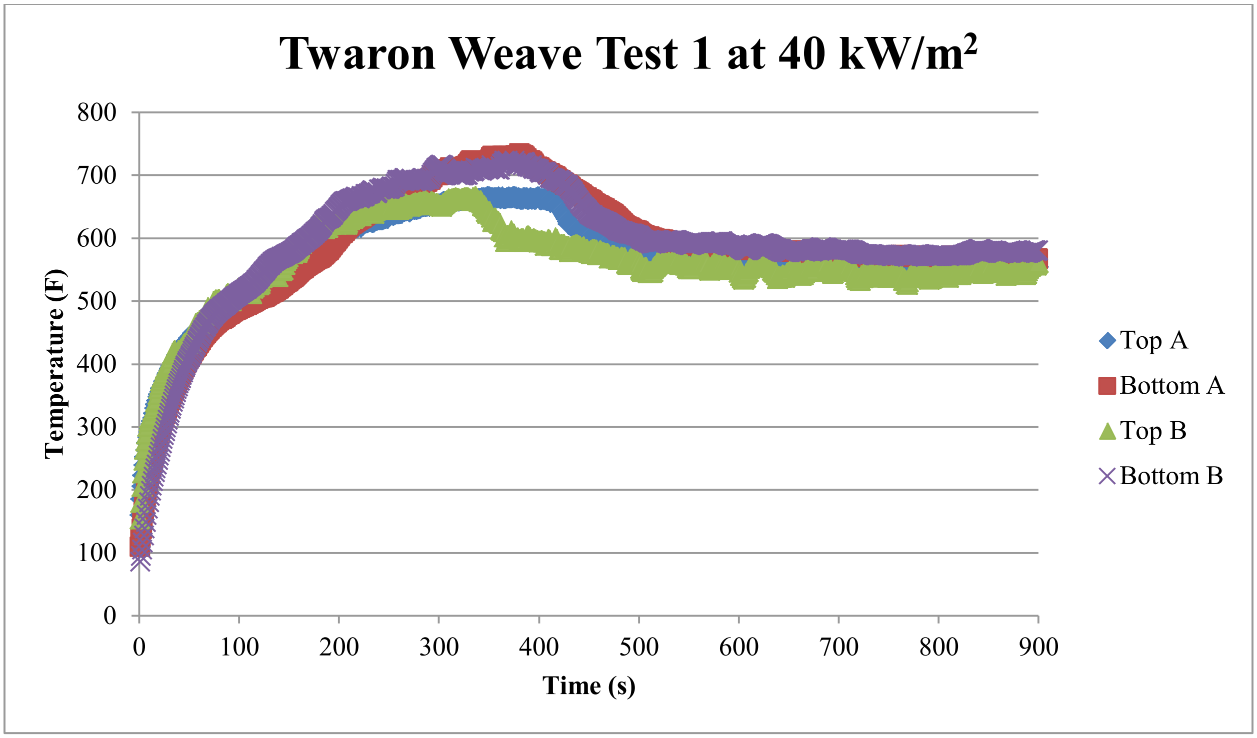


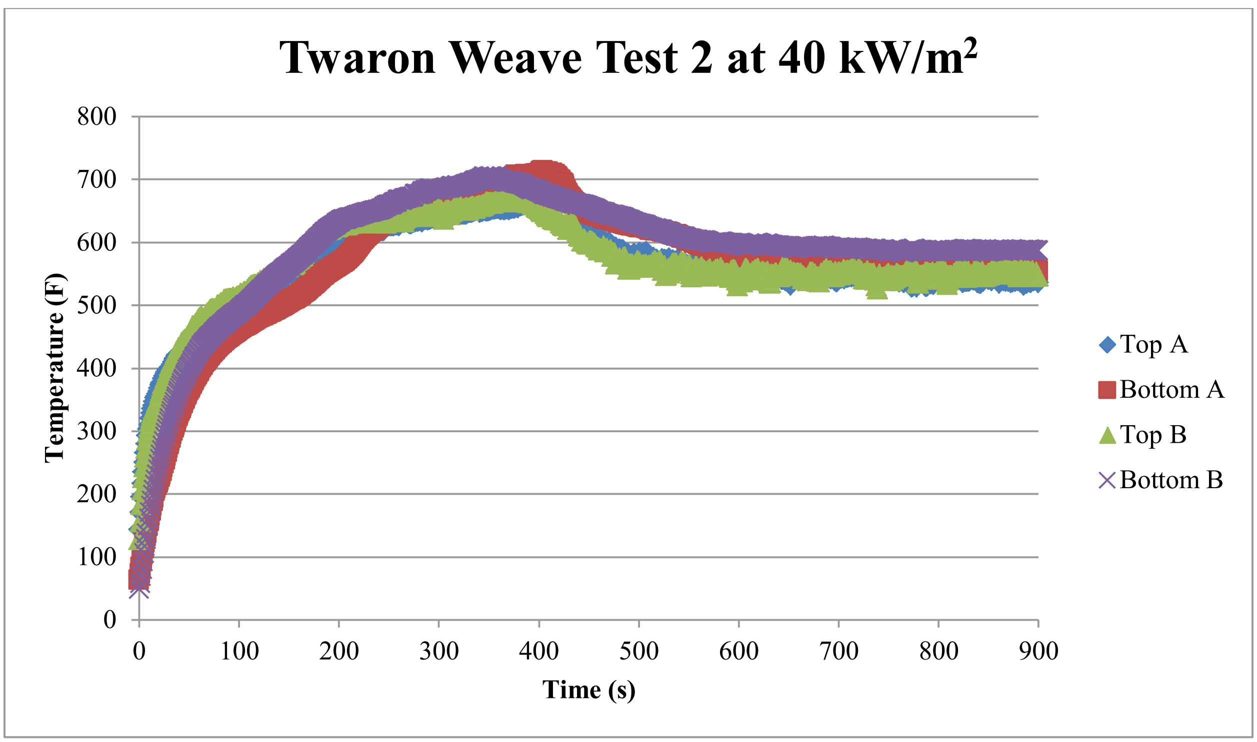

PBI Matrix Test 1 at 40 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Bottom A
Top B
Bottom B

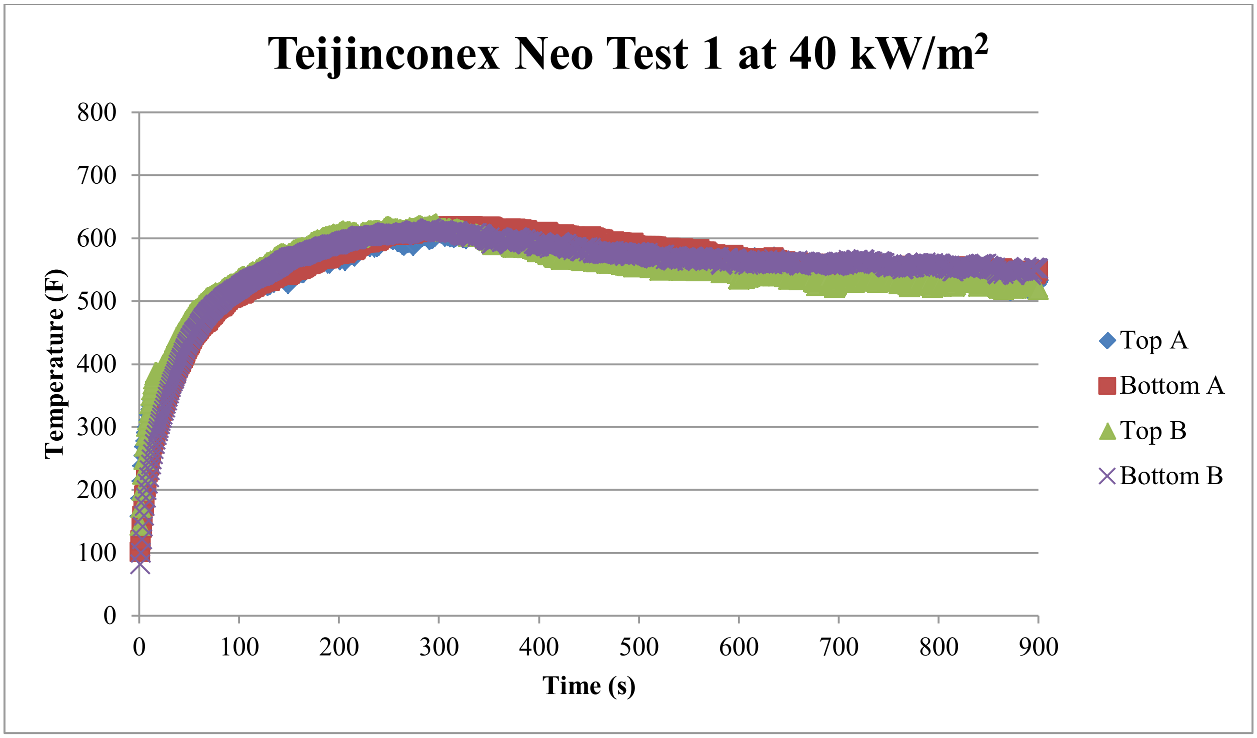

PBI Matrix Test 2 at 40 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

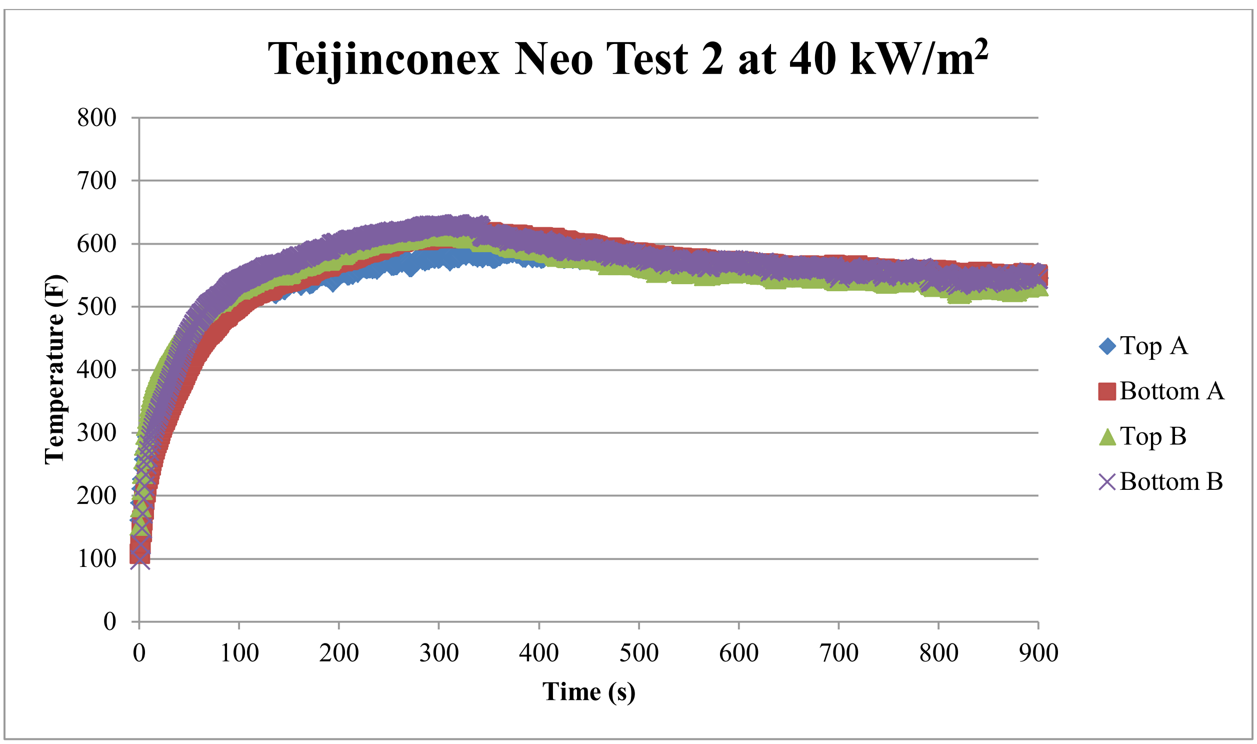

Twaron Knit Test 1 at 40 kW/m²
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B

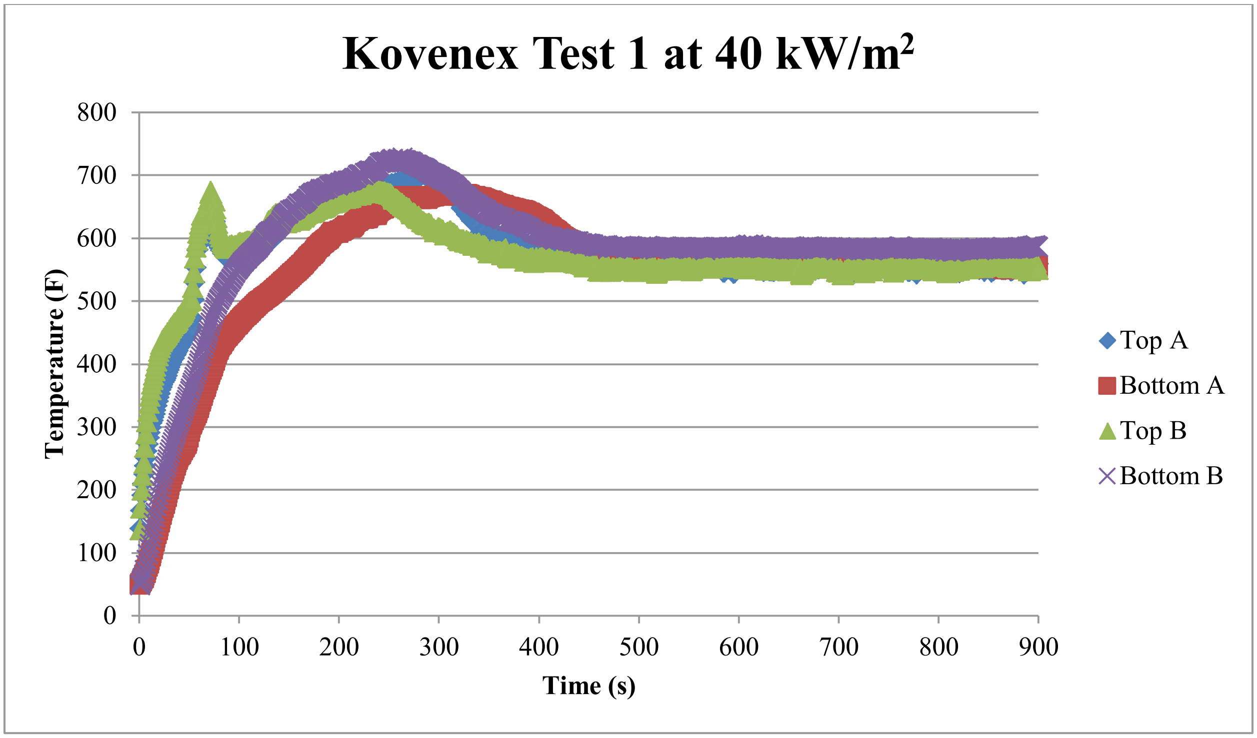

Twaron Knit Test 2 at 40 kW/m²
Temperature (F)
Time (s)
0
100
200
300
400
500
600
700
800
900
Top A
Bottom A
Top B
Bottom B


Twaron Weave Test 1 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

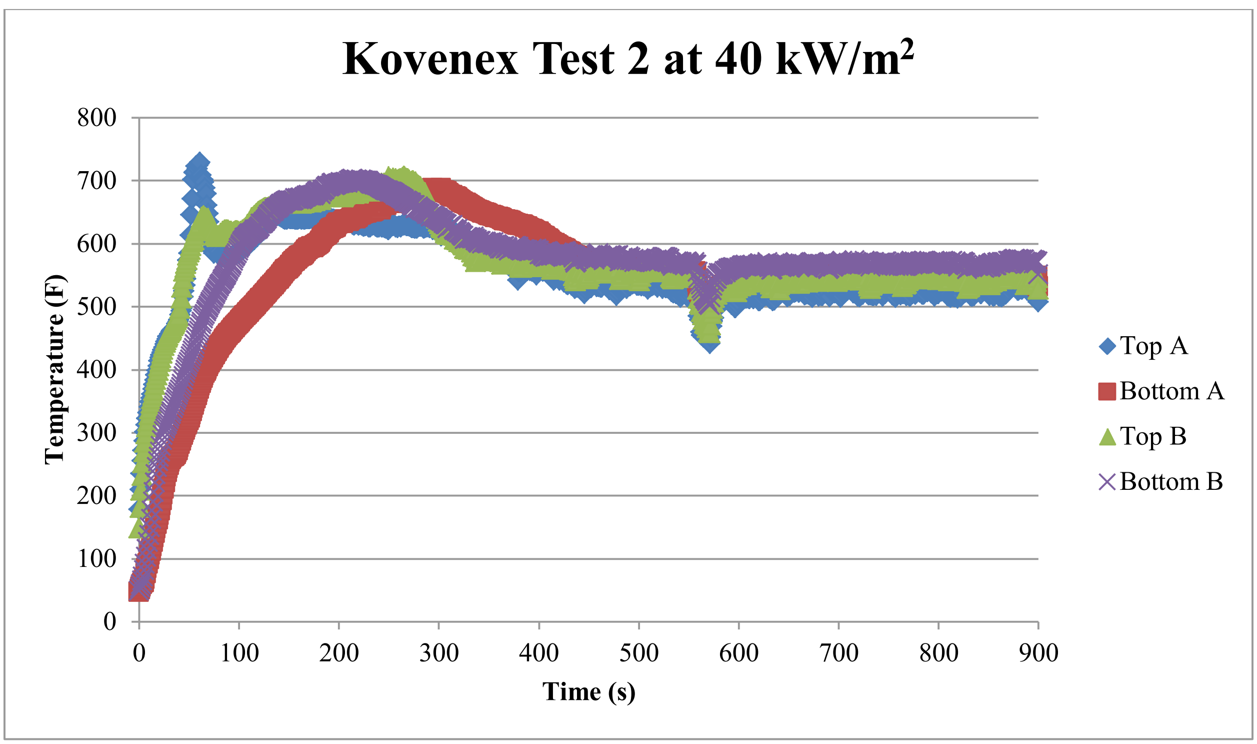

Twaron Weave Test 2 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Teijinconex Neo Test 1 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

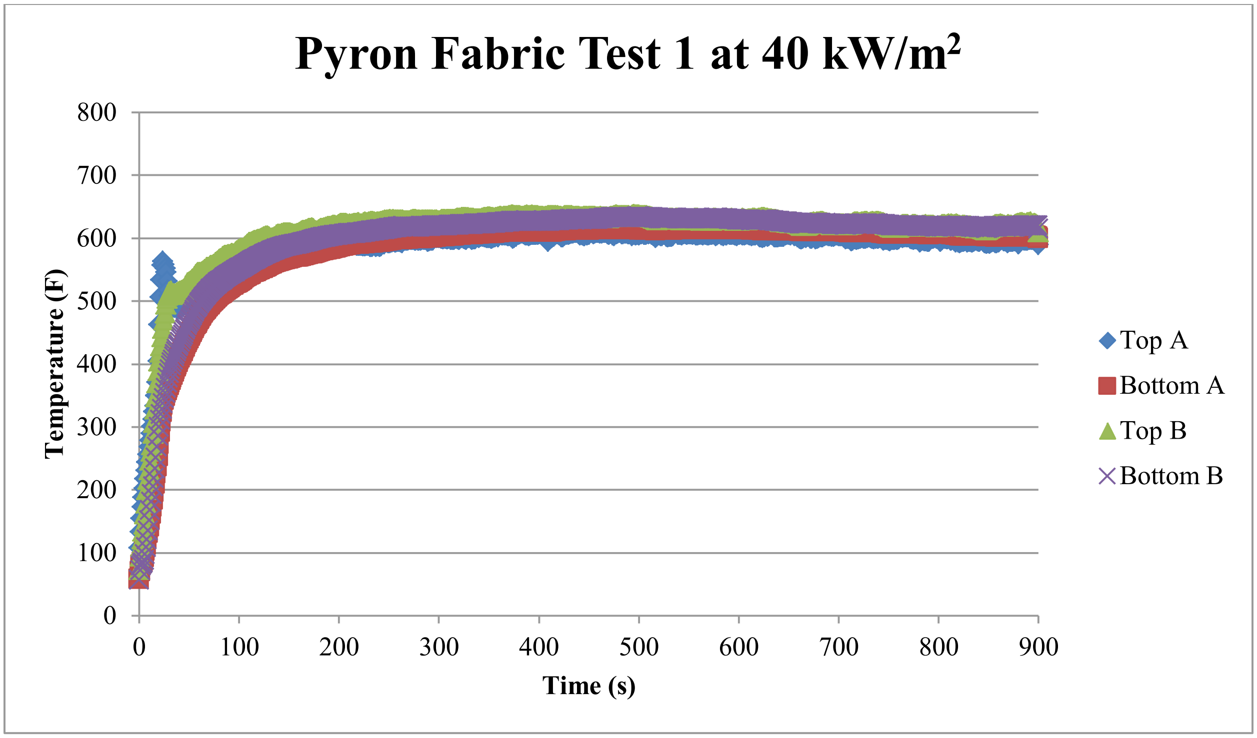

Teijinconex Neo Test 2 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

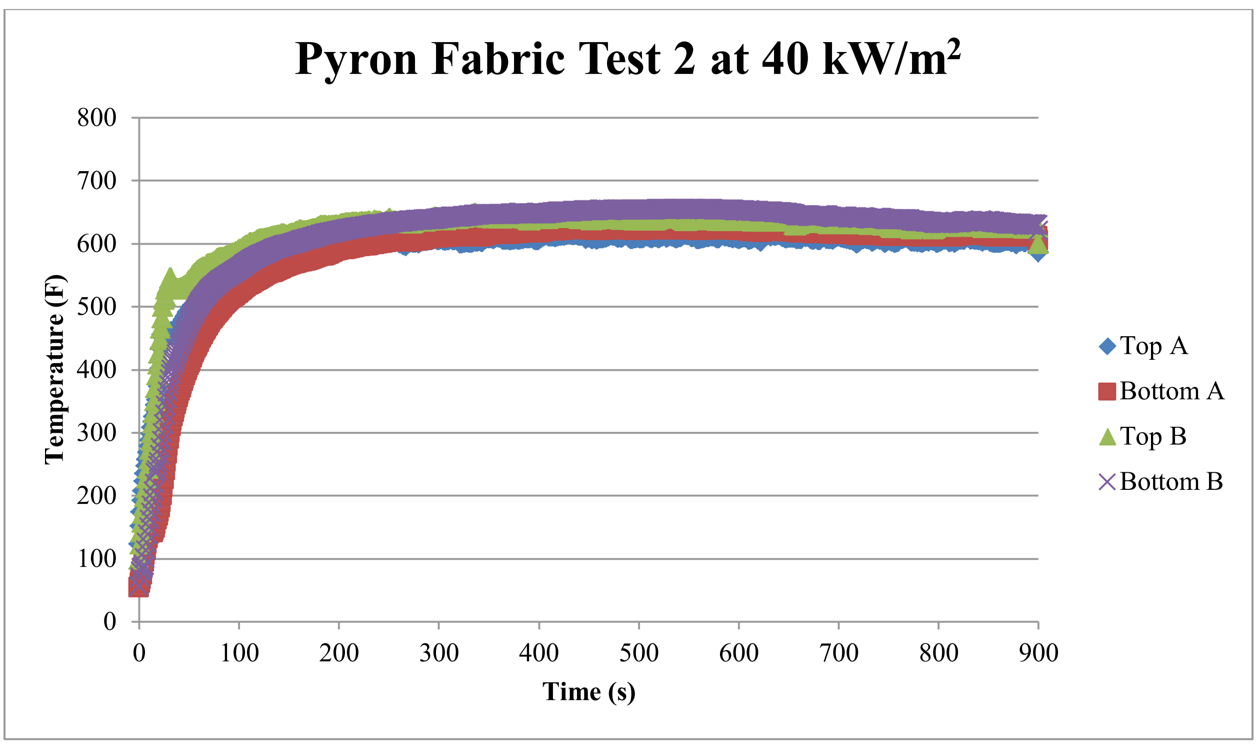


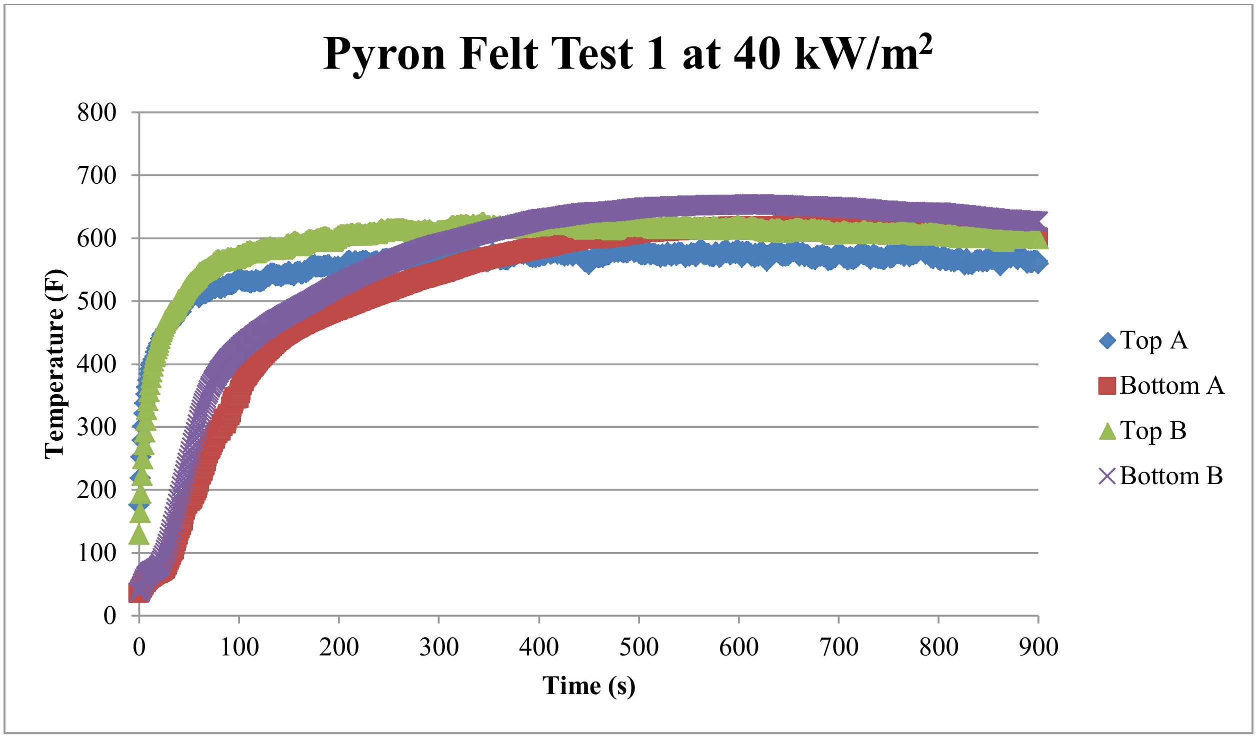
Kovenex Test 1 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

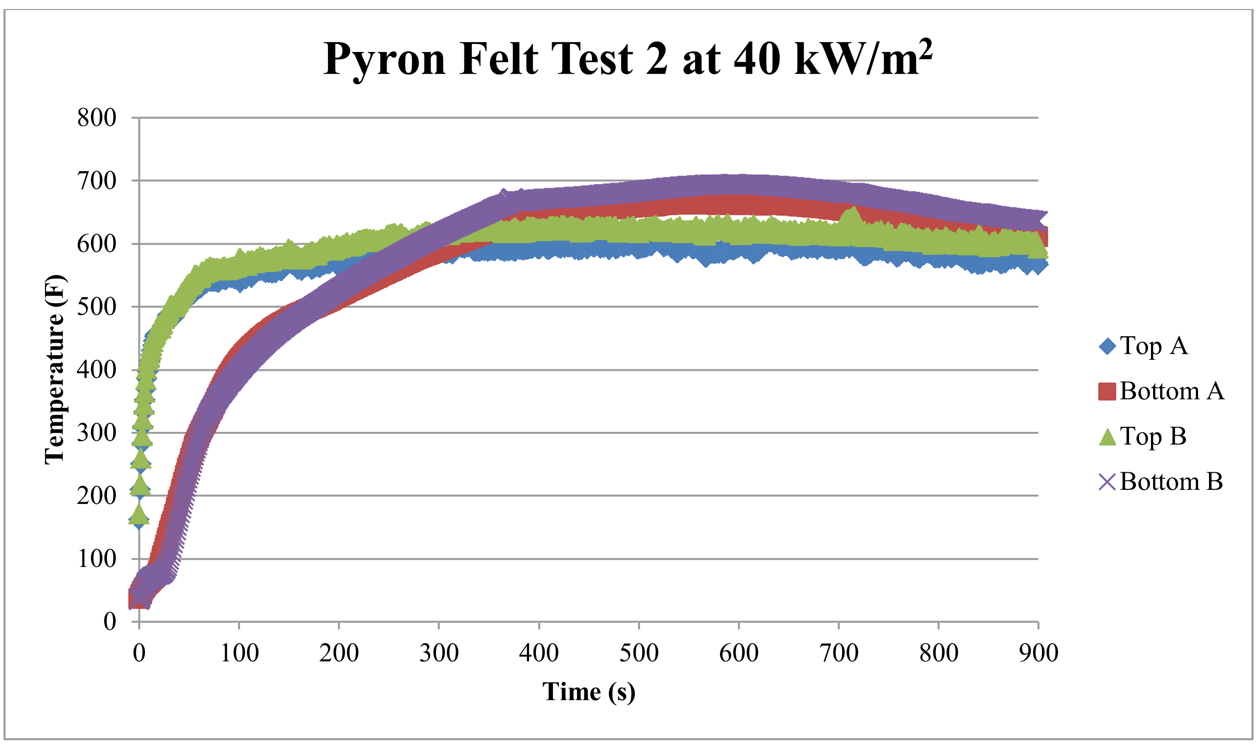


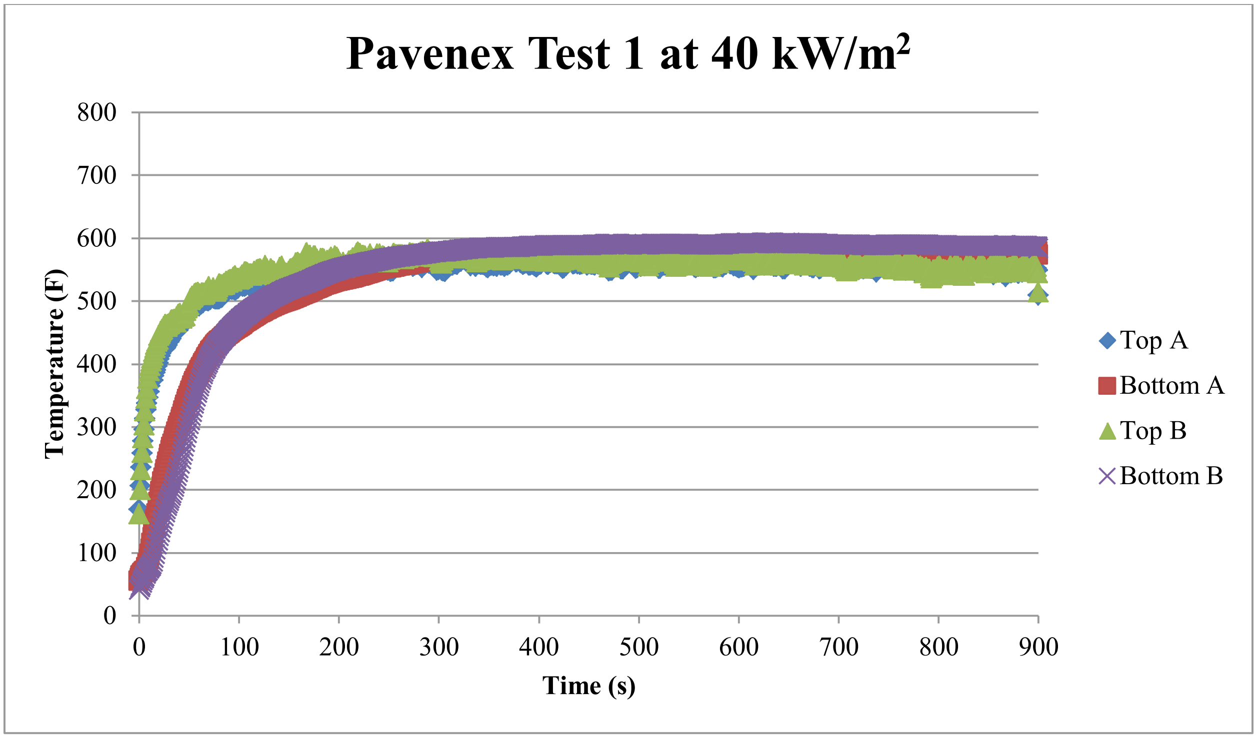
Kovenex Test 2 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

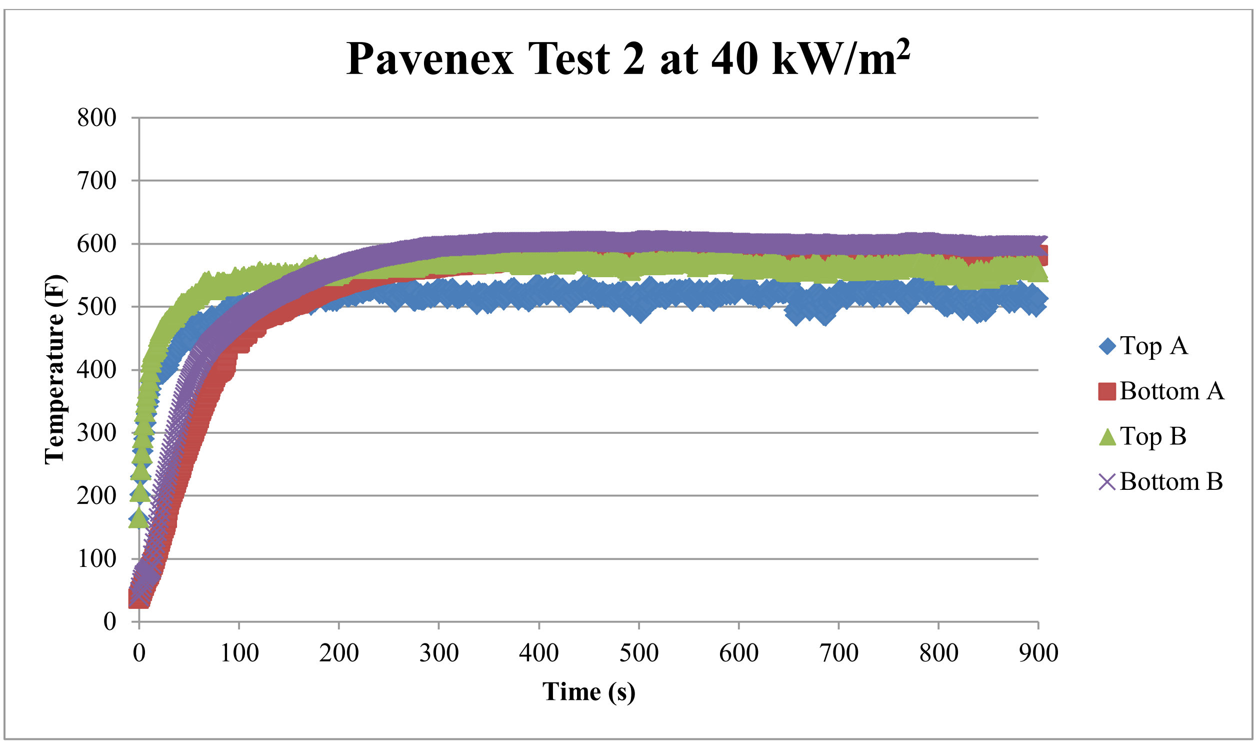

Pyron Fabric Test 1 at 40 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

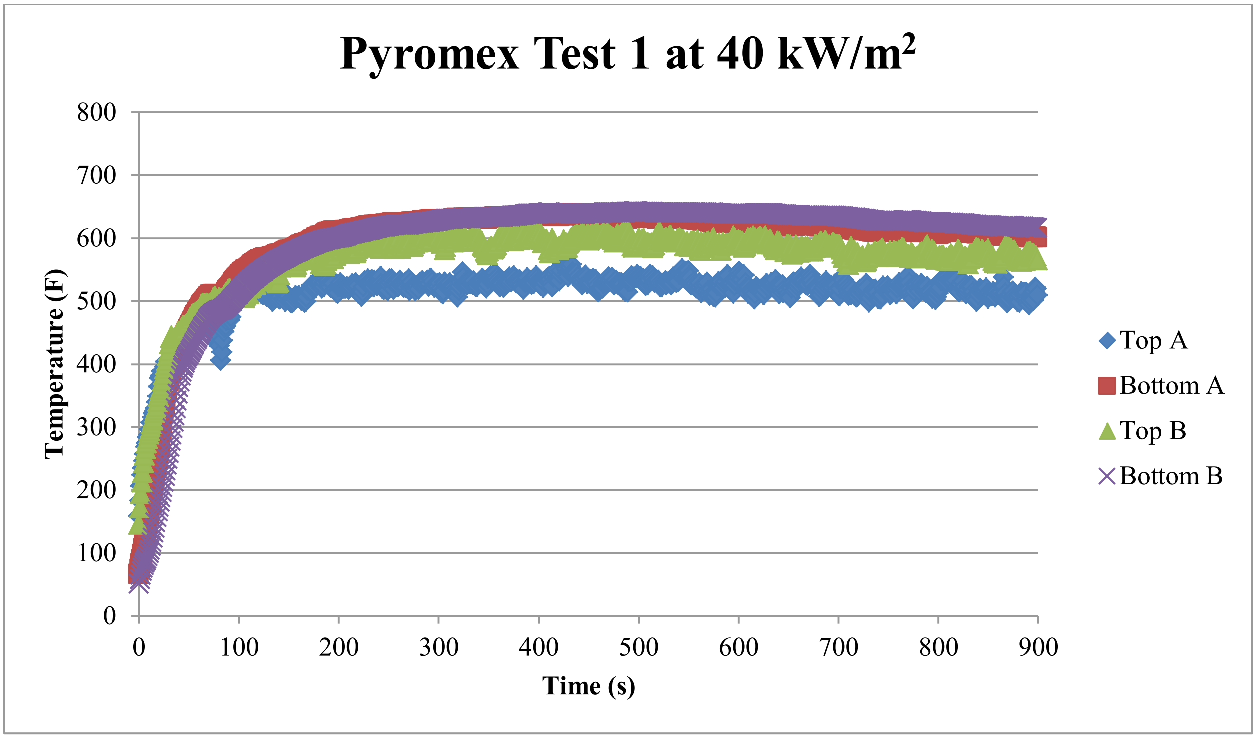

Pyron Fabric Test 2 at 40 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

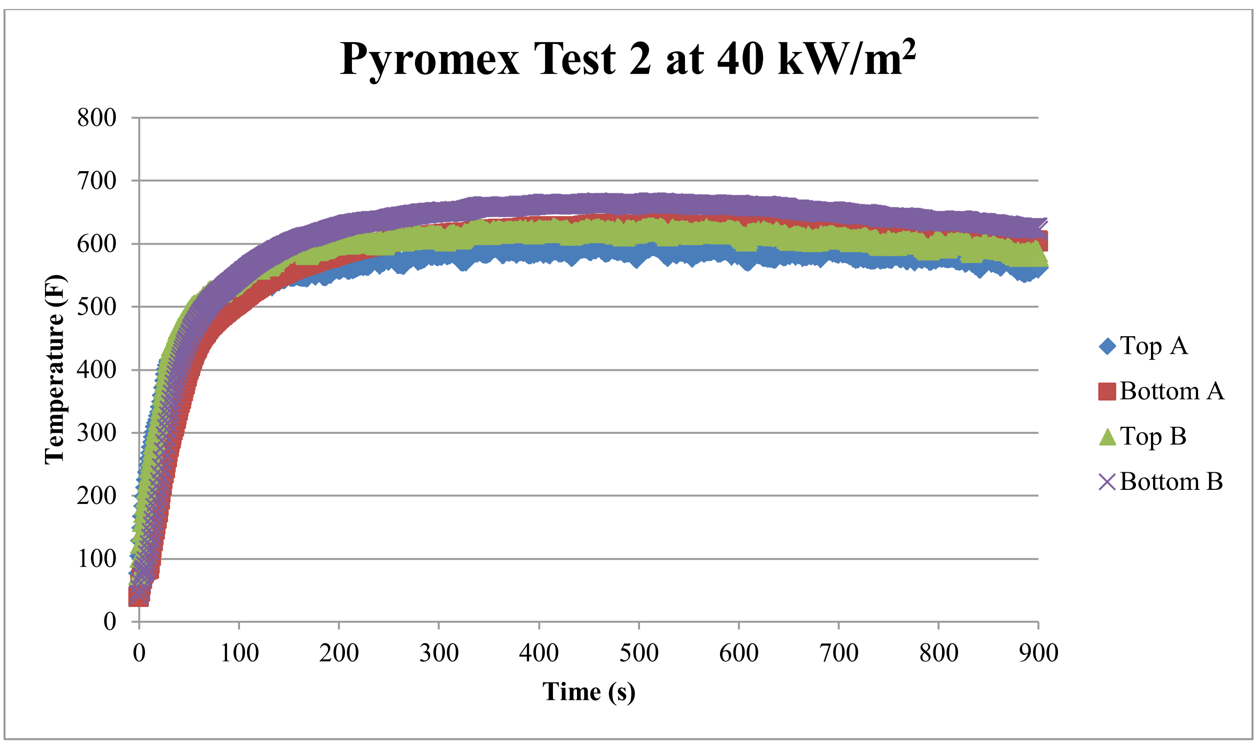

Pyron Felt Test 1 at 40 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Pyron Felt Test 2 at 40 kW/m2
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Pavenex Test 1 at 40 kW/m2
800
700
600
500
400
300
200
100
0
Temperature (F)
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Pavenex Test 2 at 40 kW/m2
800
700
600
500
400
300
200
100
0
Temperature (F)
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Pyromex Test 1 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B


Pyromex Test 2 at 40 kW/m²
Temperature (F)
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
Time (s)
Top A
Bottom A
Top B
Bottom B

Appendix F: Average Percent Mass Loss, Average Ignition Time, and Standard Deviation

This Appendix contains all data points recorded along with averages and standard deviations.

Table 14: Average Percent Mass Loss at 20 kW/m^2

Material	20 kW/m2			
	Percent Mass Loss			
	Test 1	Test 2	Average	St. Dev.
PBI Gold	8.03	8.47	8.25	0.31
PBI Matrix	5.10	5.67	5.38	0.40
Twaron Knit	1.44	1.51	1.47	0.05
Twaron Woven	2.12	3.11	2.62	0.70
Teijinconex	7.19	7.45	7.32	0.19
Kovenex	27.01	28.03	27.52	0.72
Pyron Fabric	18.23	17.71	17.97	0.37
Pyron Felt	16.97	16.70	16.83	0.19
Pyromex	11.96	12.84	12.40	0.63
Pavenex	16.94	17.53	17.24	0.41

Table 15: Average Percent Mass Loss and Ignition Time at 30 kW/m^2

Material	30 kW/m2							
	Percent Mass Loss				Time to Ignition			
	Test 1	Test 2	Average	St. Dev.	Test 1	Test 2	Average	St. Dev.
PBI Gold	18.36	40.25	29.30	15.48	None	None	None	None
PBI Matrix	32.68	20.55	26.62	8.58	None	None	None	None
Twaron Knit	30.60	26.98	28.79	2.56	547	537	542	7.07
Twaron Woven	46.15	62.46	54.30	11.53	519	556	538	26.16
Teijinconex	45.35	37.35	41.35	5.66	None	None	None	None
Kovenex	53.90	59.64	56.77	4.06	840	790	815	35.36
Pyron Fabric	37.36	39.94	38.65	1.83	None	None	None	None
Pyron Felt	33.14	34.55	33.84	1.00	None	None	None	None
Pyromex	38.20	37.33	37.76	0.62	None	None	None	None
Pavenex	35.45	33.33	34.39	1.50	None	None	None	None

Table 16: Average Percent Mass Loss and Ignition Time at 40 kW/m^2

Material	40 kW/m2							
	Percent Mass Loss				Time to Ignition			
	Test 1	Test 2	Average	St. Dev.	Test 1	Test 2	Average	St. Dev.
PBI Gold	78.74	87.08	82.91	5.90	127	145	136	12.73
PBI Matrix	90.28	87.35	88.82	2.08	153	146	150	4.95
Twaron Knit	82.38	77.46	79.92	3.48	122	130	126	5.66
Twaron Woven	95.61	92.93	94.27	1.89	163	135	149	19.80
Teijinconex	93.87	84.94	89.40	6.31	None	None	None	None
Kovenex	93.52	89.33	91.43	2.97	54	42	48	8.49
Pyron Fabric	75.79	80.00	77.90	2.98	20	21	21	0.71
Pyron Felt	60.55	69.81	65.18	6.55	None	None	None	None
Pyromex	68.77	66.67	67.72	1.49	None	None	None	None
Pavenex	64.84	65.23	65.03	0.28	None	None	None	None